12-5-2006

Multi-Variant analysis of real-world environmental variables affecting image fading on outdoor synthetic inkjet substrates

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Multi-Variant Analysis of Real-World Environmental Variables Affecting Image Fading on Outdoor Synthetic Inkjet Substrates

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A thesis submitted in partial fulfillment
of the requirements for the degree of Master of Science
in the School of Print Media in the College
of Imaging Arts and Sciences
of the Rochester Institute of Technology

May 2006

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Secondary Thesis Advisor: Professor Franziska Frey

Title of Thesis:

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Acknowledgements

I would like to thank the Roland DGA Corporation for their sponsorship and support of this research. Without their generous donation this research would not have been possible. I would also like to extend a special thank you to Eric Lehman for contacting Roland DGA Corporation on my behalf, Greg Barnett for his assistance with accessing the roof, my advisors, Mary Anne Evans and Scott Williams. Thank you to my friend, Dimitrios Ploumidis for his advice and help. Without these generous people the completion of this research would not have been possible. My sincere thanks goes out to all of you.

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Abstract

The permanence of large format, outdoor inkjet signs is a concern for many advertisers and companies creating signs that will be displayed for years or months in such an environment. The permanence industry has focused their research on using equipment to simulate these outdoor conditions the prints face to gauge their fading properties. This research took a more direct approach by placing the prints in an actual outdoor environment and tracking the rate of color change (ΔE_{ab}), and the environmental variables. A multiple regression analysis of the data was then used to create prediction models and to eliminate environmental variables which did not affect the fading.

The multiple regression analysis was able to create a prediction model for only two of the patches tested on one of the substrates. The test included three substrates (uncoated vinyl, coated vinyl and Tyvek (DuPont)) and ten color patches (cyan, magenta, yellow, black, red, green, blue, two grays, and plain substrate). The successful models were for the measured substrate patch and the cyan patch on the ESM (uncoated vinyl) substrate. The model showed that the substrate patch was affected by the average high and low temperatures and by the amount of time exposed in weeks. A second model showed that the cyan patch on the ESM substrate was affected by the UV index and the

amount of time exposed in weeks. Further examination of the study showed that the ESM substrate was the most stable under the experiment conditions out of the three substrates. Cyan ink was the least stable ink on the Tyvek (DuPont) and coated vinyl and that the coatings on the substrates play a role in their ability to maintain color integrity of the print.

Chapter 1

Introduction

Introduction

The large-format inkjet market in the United States is changing quickly. Two of the fastest growing areas of the large-format inkjet market presently are eco-solvent and solvent inkjet printers for outdoor signs (Flippin, 2004). A survey conducted by Web Consulting discovered that, of companies planning on purchasing a new printer, thirty percent were planning on purchasing a solvent or eco-solvent large-format printer (LeClaire, 2005). These companies are hoping to add new business and attract new clients through the additional ability to print outdoor signs (Flippin, 2004).

Outdoor signs are subjected to weather variables — rain, humidity, sunlight, ozone, etc — which cause fading at higher rates outdoors than they do indoors. Due to the harsh exposure of outdoor signs, permanence has become a critical issue in this area of the printing industry. In general, permanence for these types of signs is predicted using accelerated testing. Accelerated testing has its benefits and its disadvantages. The benefits of accelerated testing are the speed with which the data is gathered. This speed allows for the data to still be applicable once it is obtained. The problem with accelerated testing is that it may give misleading results caused by problems such as reciprocity failure or the limit of only testing a couple of variables at a time rather than all of them at once. Outdoor exposure testing is a much-needed addition to such testing that will enable advancements and improvements in the technology (Everett, 2001). This experiment shows the information and insight that is gained from outdoor "real-world" testing of large-format inkjet, eco-solvent signs.

Problem Statement

The fading property of print on three different synthetic banner substrates — Economy Scrim Banner Blockout, Lightweight Banner Vinyl, and Tyvek Water Repellent Banner (DuPont) — when exposed to outdoor environmental variables — precipitation, uv index, temperature, pollution, and humidity— was examined for correlations between the change in color of either the base or the ink and the environmental variables the printed substrates were exposed to. A Roland SolJet Pro II V, with a six-color eco-solvent ink set, was selected as the print engine. A novel multi-variant statistical approach was applied to the research in order to correlate the uncontrolled environmental factors and print fading. This was the first known study to learn how "real world" conditions impact print quality. This study will aid future researchers conducting accelerating testing to better understand which variables should be tested and which combinations of variables should be tested.

Reasons for Interest

This study involved the intersection of two areas of interest of the researcher: printing and advertising. The researcher has an undergraduate degree in advertising photography and became involved in printing on large-format printers, such as the Epson 9600. The researcher has furthered her education by studying for a Master's Degree in Print Media. This combination of study led to an interest in the archival nature of inkjet printer substrates.

A survey of the literature on research pertaining to large-format inkjet prints and the rate of fading in outdoor conditions was conducted. Research on the permanence of paper-based substrates was found, but only limited research was found on non-paper (synthetic) substrates used for outdoor signage, specifically in real-world environment testing. This prompted the researcher to conduct further research into the area of outdoor signage and synthetic substrates.

Explanation of Problem

The problem studied was the fading property of prints on three different synthetic substrates (Economy Scrim Banner Blockout, Lightweight Banner Vinyl, and Tyvek Water Repellent Banner [DuPont]) when placed in an exposed outdoor display environment. The printed ink on the three different substrates was compared to see which faded the fastest and under which conditions. A second set was kept in dark storage for comparison.

Chapter 2

Theoretical Basis of the Study

Introduction

The reasons behind measurement choices, test target choices, and the point when fading is determined to have occurred are stated and discussed in this section. These factors set up the method that was used for this research and can be used to later create similar research or recreate this study.

Optical Density Fading

Optical density is defined as an ink film layer's imperviousness to light. Mathematically, it is the negative logarithm (base 10) of the reflectance ratio. Optical density is one of the methods of measurement used to determine the amount of color in a print; the lower the density of a print, the smaller the amount of color. As a print fades over time, the density of a particular patch of ink will begin to decrease, causing the ink to appear less vibrant and "faded". This decrease in density can be caused by many different factors, the most common of which is sunlight bleaching the pigments or dyes. Permanence testing begins with measuring the density of a patch that has been printed and not exposed to light, and then measuring the patch after light exposure; the change in density is related to the amount of color that has disappeared during the testing (HP, 2004).

Test Target

Test targets are variables placed onto a press sheet that can be measured and have a known value or distinctive appearance (Sharma, 2004). Test targets can be used to analyze a range of different problems — from registration to screening — and provide assurance that a press run has been done correctly. Test targets can also establish a set of known variables for a specific press or research experiment (Chung, 2005). In the case of this research they were used to establish CIELAB values and density values before the fading occurred.

The test target created for this study consisted of patches of cyan, magenta, yellow, black, red, green, and blue and two gray patches (one of CMY and one of CMYK). The basis for the choice of these colors was that these colors make up the primary and secondary colors that are used to create all other colors. Red, green, blue, and the two grays are made from mixing the primary subtractive colors, or the colors in the ink set (cyan, magenta, yellow, and black); this allowed the researcher to check for catalytic fading, which occurs when one dye trades energy with another dye while being mixed together in a print. Due to the nature of the printer used, the cyan and magenta inks used in the study may not be pure; an additional ink may be mixed in. The six-color ink set uses a light cyan and a light magenta dye, in addition to the four regular inks

(CMYK). The printer was set to default which allowed the light cyan or light magenta to mix in with the regular primary inks. This allowed the study to more closely mirror what would occur in a real life application.

Colorimetry

Colorimetry is the measure of how color is perceived, and the International Commission on Illumination (CIE) sets forth the standards for color measurement. However, measuring color in a print does not validate whether the color appearance is acceptable; only the human eye is capable of judging color acceptance. The CIE has specific settings for the illuminants and a standard observer that are to be followed precisely in order to ensure that measurements can be compared. They have also developed several different color spaces, including the one to be used for this study, CIELAB (Chung, 2005).

CIELAB

The color space, CIELAB (L* a* b* for short), is based on opponent color theory and is one of the languages used to specify color. L* is the lightness, a* is the redness or greenness, and b* is the yellowness or blueness. A positive a* signifies red, and a positive b* signifies a yellow. CIELAB can be best described as a specification of color, as viewed by human observers that can accommodate any color.

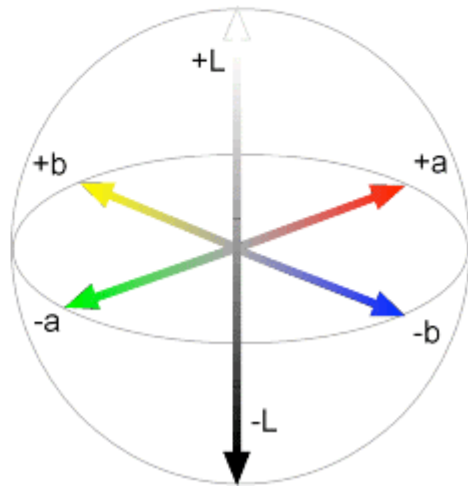

Figure 1. 3D Diagram of CIELAB color space
(Source: http://www.tasci.ac.uk/images/cielab.gif)

CIELAB was chosen for the study because it is a perceptual color space which replicates mathematically what the human eye observes. CIELAB is based on tristimulus integration, where the light source, object, and observer are used as functions in the calculations. The observer is based on the standard observer for either 2 or 10 degrees and was determined by the CIE. As shown in Figure 1, CIELAB specifies the location of a color in a 3D diagram (Sharma, 2004). This color space is useful in calculating a color change within a print or when comparing two different prints (Chung, 2005). For this study, the illuminant D50 and a standard observer of 2° were chosen for the measurements.

Δ E_{ab}

Delta E (denoted ΔE) is a numerical value that indicates the numerical color difference between two colors in a color system such as CIELAB (Kipphan, 2001). It allows for the quantification of a color difference, rather than for a qualitative expression.

ΔE is a statement of the difference between two patches of color, and, it is only understood once the classification system and formula used to calculate it are known. In this study, the color classification system used was CIELAB, and the corresponding formula used for calculating ΔE_{ab} was $\Delta E_{ab} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$. The ΔL^*, or change in L^*, was obtained by taking the L^* measurements and subtracting them as follows $\Delta L = L_1 - L_2$, the same formula was used for finding Δa^* and Δb^* (Kipphan, 2001).

The bigger the ΔE_{ab} between two colors; therefore two colors with a large ΔE_{ab} will look completely different while two colors with a small ΔE_{ab} will look almost the same. A ΔE_{ab} of one is defined as a just noticeable difference (JND); it is the point at which a trained eye discerns the difference between the two colors (Sharma, 2004). Some people are more sensitive to color differences than others and can detect differences at different ΔE_{ab}s. Variables such as training, color blindness, age, and gender can influence this sensitivity (Kipphan, 2001).

Reason for ΔE_{ab}

ΔE_{ab} was chosen over ΔE_{00} for color comparison for several reasons. The main reason emerged during an interview conducted with color scientist, Mark Fairchild, who recommended the use of ΔE_{ab}. Fairchild reasoned that since the researcher was always comparing like colors (for example red to red) and not comparing different colors, which type of ΔE used, was not important. It was a tool for comparison and either one would do the job correctly. Another reason ΔE_{ab} was chosen is that ΔE_{00} uses a very complex equation. This equation includes corrections for non-uniformities in the perception of color differences across the CIELAB color space. For example, yellow differences are more difficult to detect than magenta differences with the same numerical ΔE. The complexity of the equation would not allow for any additional information to have been concluded from the research and would have only complicated procedures. This complication of procedures adds additional margins for error that were eliminated by using the simpler equation (Fairchild, 2005).

Endpoints

When evaluating the results of a fading study, endpoints may be chosen to determine whether or not fading has taken place. Endpoints are not necessarily the end of a useful photograph or print; they are merely a step in the aging process of a print. The print or photograph may continue to have some information after fading occurs that is still readable or viewable (Wilhelm, 2004). An agreed-upon endpoint among researchers facilitates research and allows for different studies to be compared. However, different researchers use different endpoints for their testing, but with the knowledge of what their endpoint settings are, their study can be evaluated based on the designated endpoints (McCormick-Goodhart, Shklyarov, & Wilhelm, 2004).

The Wilhelm Image Research (WIR) uses endpoint criteria that have a higher tolerance for loss in yellow than they do for magenta or cyan. This is because the human eye is most tolerant of changes in yellow and is least tolerant of changes in magenta. The explanation for this difference in tolerances is that yellow contributes the least in the contrast of images, while magenta accounts for the most contrast (Wilhelm, 2004). This specification for endpoints from the WIR v3.0 takes into consideration the human eye sensitivities for every color. It has a specific endpoint for every color (Ishibashi, Ishizuka, Machida, & Shibahara, 2004).

International Standards Organization (ISO) 10977 currently specifies a 30% loss of density of any primary colors, a 15% color balance change of a neutral patch, and a 0.10 density increase in Dmin as an illustrative endpoint for color reflection prints. ISO endpoints work well for a simple estimation of print life (Ishibashi, et. al, 2004). The ISO endpoints do not accommodate for the way the human eye sees different colors but are much simpler to use. The endpoints chosen for this study were the ISO endpoints.

Climate

The experiment was conducted in Rochester, New York. The climate in this location played a key role in the outcome of the experiment. The experiment measured the affect of different weather variables on the printed piece; changing weather conditions were measured as were their affects on the printed piece. Rochester is bordered by one of the Great Lakes, Lake Ontario, which has a profound impact on the weather. Rochester is considered part of upstate New York and thus has a climate which experiences all four seasons during the year. The experiment was from late fall, through winter.

A significant amount of snowfall — more than anywhere else east of the Rockies — occurs during the winter season in upstate New York due to the proximity of Lake Ontario, which causes lake effect weather. Lake effect snow and rainstorms occur as moisture develops over the large body of water, then moves inland, and releases snow onto the surrounding areas. The lake effect causes rapid shifts in moisture and temperature in the area (About Rochester, 2005). All of these variables make for an interesting experiment relating to weather; the test prints were exposed to a variety of temperature ranges and weather extremes.

Chapter 3

Review of Literature

Introduction

The permanence of outdoor inkjet prints is the focus of this research, which encompasses everything from environmental regulations over emissions, ink and substrate type, to different permanence tests that can be conducted. Environmental regulations play a role in the print industry and in this research because they preside over the type of inks that can be used. The type of fading tests that exist in the industry, as well as any problems with them, will be reviewed. The review of the literature on this subject led to the conclusion that a lack of information on permanence of prints on synthetic substrates for outdoor display existed. All of the aforementioned information is the basis for the design of the permanence test that will be conducted.

Background Information on Inkjet Printers

Inkjet printers were first introduced in the late 1960s. Canon has claimed that they invented the first drop-on-demand inkjet printer (the “bubblejet”) in 1977. The bubblejet was invented when a Canon employee, working in a lab, touched a syringe of ink with a soldering iron, and a bubble was forced out by the heat (All About Inkjet, 2005). This led to the development of the first inkjet printer, released later that year.

There are two main types of inkjet printers: drop-on-demand (DOD) and continuous inkjet. DOD printers can be further broken down into subcategories of thermal inkjet and piezo inkjet (Kipphan, 2001). All prints evaluated for this study were printed with the Roland SolJet Pro II V, which uses piezo inkjet technology. Piezo inkjet works by mechanically deforming the jet chamber, which causes a change in volume until a drop is squeezed out onto the page. Due to the manner in which piezo inkjet systems work, a broader range of ink formulations can be used (Kipphan, 2001). Piezo inkjet printing is now commonly used for making many items including banners, billboards, and trade show displays (Adkins, 2001).

Originally, large-format inkjet printers were created to generate proofs of jobs being sent to other presses. These inkjet printers were never intended to be used by consumers for any job where permanence was important and thus had a problem with permanence. The technology was designed to be an economical solution for jobs that had a short-term life expectancy (Pringle, 2000). Now, with the growing field of large-format inkjet printers being used for outdoor signage, a greater emphasis is being placed on the permanence of the prints (Lontz, 2003). The most common types of large-format inkjet printers are aqueous, solvent, eco-solvent, and UV curable (Halkyard, 2004).

Increased productivity with inkjet printers has caused a shift toward using large-format inkjet printers for more than just proofing. They are now being used for all types of jobs, including outdoor signage. Sales for large-format inkjet printers were $19 billion in 2002 and have been predicted to grow by almost $30 billion in five years. When examining these figures, it becomes obvious that there is a growing market in this area. In 2003, the inkjet substrate market was comprised of 59% non-paper based substrates, which is a 10% increase from 2002; an increased strength in pigment-based systems and improving longevity has allowed for this expansion in the inkjet segment of the printing industry (Hinderliter, 2004).

The following additional factors affect this increase in the large-format market: marketing that focuses on cross-media communications, advances in inkjet technology, and printers who are trying to become a one-stop shop for print buying (Pellow, 2005). Companies are expanding their businesses to include large-format inkjet printing to gain more clients and to prevent current clients from going elsewhere. Wide-format digital printing will be a prominent factor in future industry growth, as differentiation and competitiveness increase within the industry and margins decrease (Gustavson, 2005).

Recent advances in inkjet technology have allowed eco-solvent printers to enhance the growth potential for large-format inkjet printing. Eco-solvent printers will be able to compete in this area of growth, due to the fact that they are able to print on a large variety of substrates that are both coated and uncoated. This prediction of growth is due to the eco-solvent inkjet printers' speed and the high quality images that they produce now (Gustavson, 2005). As states are increasing their environmental regulations, printers looking to conform to these new standards are turning to eco-solvent printers as a solution.

Environmental Regulations

The Environmental Protection Agency (EPA) brought forth new ozone standards in 2003 that all companies must comply with by 2021. The new standards call for a reduction in ozone from 0.12 parts per million to 0.08 parts per million over an eighteen-year span and will cause companies to significantly reduce their emissions of volatile organic compounds (VOCs). The reason for the call to reduce VOCs is that they contribute to global warming and they have been implicated in a variety of health problems found in people working in direct contact with them. Monitoring emissions in printing companies is now the norm. These regulations have affected every aspect of their production, from storage to disposal of waste. The pressure for companies to comply with environmental standards is intensifying, due to increased monitoring by both state and local governments, along with harsher punishments and fines for non-compliance (Cagle, 2003). The risk of non-compliance to these standards will result in fines and a generally poor public opinion of those companies. This could have a devastating effect on the amount of business a company does and attracts.

All of the pressure of conforming to the EPA standards and Occupation Safety and Health Administration (OSHA) standards has caused the manufacturers of large-format inkjet printers to search for other options (besides solvent printing) for outdoor applications with large-format inkjet. One option developed by manufacturers is an eco-solvent ink set for large-format inkjet printers (Antoniak, 2005). Companies are looking toward the future with their purchases of eco-solvent printers, as environmental regulations brought by the EPA and OSHA are increasing. Companies are attempting to go beyond the necessary compliance, in hopes that they will need to make fewer changes to meet future regulations; companies are looking at the lifecycles of their equipment and making certain that more upgrades are available to continue conforming to regulations (Cagle, 2003). Manufacturers of eco-solvent ink sets are continually working to improve this type of ink set, to remain ahead of the compliance regulations.

Inks

All inks have similar types of formulation components; they all contain a colorant, vehicle, additives, and carrier substances. However, different chemicals can be used for each of those parts that cause each ink to have different properties, which can affect light-fastness. Colorants are comprised of either pigments or dyes. A pigment is an organic or an inorganic colored substance that is insoluble in the vehicle (suspension liquid). Pigments need a vehicle to bind them to the substrate. Only 10% of the pigment particles contained in an ink are on the top layer, and it is only this 10% that is able to absorb light. This causes pigments to have better light-fastness properties than dyes. A dye is contained more in the surface layer than pigments and is in contact with more light, causing it to degrade faster.

A dye is an organic compound that is dissolved during the creation of the ink. Since dyes are dissolved into a liquid form, it allows for each of the dye molecules to absorb light, permitting a much larger range of color. In contrast, pigment particles are dispersed and encapsulated in the vehicle. The vehicle then dries onto the substrate, which allows the pigment to adhere to the substrate (Kipphan, 2001).

Inkjet devices place special demands on the inks that they utilize. The inks generally have a very low viscosity and have to be meticulously filtered to avoid clogging the nozzles in the printer heads. The low viscosity of inkjet ink causes the end result to depend upon the type of substrate used. Inkjet inks can bleed, marble, and penetrate differently. Most inkjet manufacturers overcome these problems by putting a special coating on the substrates. The coatings work by immobilizing the colorant on the surface, thus preventing the aforementioned problems (Kipphan, 2001).

There have been numerous studies done on pigment versus dye-based inkjet printers. The market has indicated that inkjet companies are switching to pigment-based printers because pigments generally give better light stable images; however, they have a reduced color gamut (Bermel & Bugner, 1999). One of the reasons that a pigmented ink is more stable than a dye-based ink is that the pigment particles are suspended in a water carrier. Pigment particles tend to be larger than the particles in a dye-based ink. Unlike a dye-based ink which has all the particles separated, a pigmented ink has the particles clumped together; this allows for one particle to be bleached, but for the color to show no signs of fading due to the multiple particles in a clump (Campbell, 2005).

Eco-Solvent

The Roland SolJet Pro II V uses a pigment-based ink set that is known as eco-solvent inks. Eco-solvent is a term that is applied to ink sets in the printing industry that are made out of milder (or fewer) solvents than normal solvent-based ink sets (Campbell, 2005). These ink sets are lower in cost than traditional solvent-based ink sets, due in part to the fact that they contain fewer solvents. Eco-solvent inks give off far less VOCs, which allows companies to have a lesser need for ventilation systems or environmental equipment in their plants (Schneider, 2005). Thus, less equipment and less expensive ink sets are two advantages of using eco-solvent ink sets.

The eco-solvent inks are a new phenomenon in the printing industry and work solely with piezo or thermal inkjet heads. The reasons for employing this type of inks are when a water-based ink does not dry fast enough, as well as when the company is not interested in using the more volatile solvent ink sets (Campbell, 2005). Eco-solvent ink sets work in similar ways as do solvent inks: they are capable of printing on many more types of substrates than water-based ink sets. They can print on both coated and uncoated substrates, although not without their problems (Schneider, 2005). Printing issues may occur with the compatibility of the eco-solvent inks and some substrates. The nature of the eco-solvent ink sets may cause some substrates to experience adhesion problems and longevity issues. Eco-solvent inks tend to be used by companies that are using a lower-end, smaller, wide-format inkjet, but wish to avoid the restrictions that are placed on them by a water-based ink when printing on non-porous substrates, specifically for outdoor graphics (Campbell, 2005).

Eco-solvent ink sets have arrived at a perfect time in the industry. Government regulations are calling for reductions in VOCs, and companies are looking for a less expensive way to meet the government's demands. Predictions have been made that the eco-solvent ink sets will continue to gain ground in the industry. It can be seen that printers are slowly switching over to eco-solvent inkjet printers or that they are making plans to do so in the near future (Schneider, 2005).

Light-Fastness

Light-fastness can be attributed to a number of different factors that affect the print, such as ink, substrate, and printer type. There are also outside forces that can affect the light-fastness of an image, such as internal reflectance, environment, and the edge effects (Allred & Schwartz, 1994). This makes testing difficult; all of the different factors need to be known in order to isolate the dependent and independent variables during testing. There are several mechanisms which affect the degradation of the prints, and all of the mechanisms must be known and understood before light-fastness can be improved (Vogt, 2001).

The tests done on inkjet prints for light-fastness are based on two different types of light: indoor and outdoor lighting. These indoor lighting and outdoor lighting conditions can be adapted from the standards of ISO 10977 (Everett, 2002). It is difficult to determine what lighting conditions should be used for different permanence tests because the conditions vary depending on the location where the print is displayed or stored, and can differ based on whether the image is framed behind glass or not. Besides lighting conditions, light-fastness can be tested through the use of a fadeometer, which tests the long-term effects of light in a shorter period of time through accelerated light exposure (Chen, Glass, Sargeant & Wang, 1999). Currently, the most widely accepted industry standard for testing light-fastness is to use glass filtered cool-white fluorescent illumination that simulates indoor display of 10 to 12 hours a day at a brightness level of at least 450 lux (Print Permanence, Epson White Paper, 2005). When testing light-fastness, it should be taken into account that different wavelengths of light cause different types of damage. Short wavelength UV causes a material to lose its strength, to crack, to become brittle, and to delaminate. Light that can be seen by the human eye (visible) will cause yellowing of the image and substrate, color loss, and color changes (Everett, 2002).

Accelerated testing is an industry standard for testing light-fastness of inkjet prints. Henry Wilhelm, a leader in image permanence, discovered that the amount of time an inkjet print is allowed to dry before testing begins will have serious repercussions on the outcome of the accelerated fading tests. Wilhelm tested different drying times on prints prior to light-fastness testing and found that the practice of allowing prints to air dry for several days before beginning testing had a serious effect on the light-fastness of the prints. He found that it causes the researchers to underestimate the light-fastness of the ink/substrate combinations (Wilhelm, 2002).

With light-fastness tests, the prints are exposed to light for a desired amount of time and under a desired light source. Delta E is then calculated according to the CIELAB scale and provides the amount of change in that particular color (Chen, et. al, 1999). The images are measured numerous times over the course of the experiment, allowing for the creation of a timetable regarding light-fastness of an image (Kwan, 1999). A curve should be created using measurements taken during the light-fastness test to determine the light-fastness estimation. A good test standard will specify which curve fit technique was used during data analysis. The failure endpoints in a light-fastness test should be estimated by either interpolation or extrapolation of the fitted curves to the failure criteria (Guo & Miller, 2001).

Humidity

Humidity-fastness is an important concern regarding permanence in inkjet printing. When an inkjet print is exposed to humidity, it affects multiple parts of the print and causes ink diffusion (dye smear or blur), density changes, and color balance changes (Artz, Hill, &Suitor, 2000). Humidity causes these changes by causing the dots either to migrate into the substrate or to join together. The migrating into the substrate of the dots will cause a loss of density, while the conjoining dots will cause an increase in density (Nishimura, 2006). Humidity can also cause the substrate on which an inkjet print is made to turn yellow because of a chemical reaction from the added moisture and the inks (Everett, 2002).

Humidity resistance for a print depends not only on the ink but also on the substrate on which it is printed (McCormick-Goodhart & Wilhelm, 2000). This causes the need for testing on both the paper and ink in order to report the humidity-fastness of an inkjet print. The place where humidity is the biggest concern is with the storage of inkjet prints. Any time the humidity is over 50% while a print is being stored in the dark, there is the highest concern for the stability of the image (Vogt, 2001).

Catalytic Fading

Catalytic fading is often found in areas that are not pure cyan, magenta, yellow or black. It occurs when primary inks or colors are mixed together in order to create another color and an outside force such as oxygen or ozone caused a reaction to occur. The reaction that occurs is a high-energy dye or pigment sharing some of the energy with a lower-energy dye or pigment. This transfer of energy will thus cause the lower-energy dye or pigment to appear faded or to have accelerated fading (Williams, 2006). The areas of an image that are medium-to-high density are where catalytic fading is most obvious, whereas in areas of low density, there is little catalytic fading. This is caused by a lower amount of inks intermixing (McCormick-Goodhart & Wilhelm, 2000).

Testing for catalytic fading does not have any preset standards as does testing for water-fastness or light-fastness. There are no specifications for catalytic fading testing, but there are recommendations from other tests conducted. One way to test for catalytic fading is by conducting a test under nitrogen and oxygen atmospheres using UV absorbers. This allows the researcher to identify reduction and oxidation mechanisms which may contribute to the reactions between the two dyes or pigments. The presence of hydrogen donors and singlet oxygen sensitizers should be avoided during testing (Doll, et al., 1998). More research into the proper testing methods for catalytic fading and standards are needed in the industry.

Outdoor Weatherability Testing

Outdoor testing of materials is an important part of permanence testing that is often overlooked. It provides information on the longevity and light-fastness of materials that can then be used to supplement accelerated testing, to make comparisons, and to check for problems such as reciprocity failure. It also provides data on exposure to different climates and weather patterns which are difficult, if not impossible, to duplicate in a laboratory. Outdoor testing is a much more involved process than is indoor or accelerated testing, as there is much more set-up and many more variables involved in it. Outdoor materials are exposed to different wavelengths of light, and the different wavelengths of light affect the materials in unique ways. Some dyes and pigments are more sensitive to wavelengths in the smaller end of the visible spectrum. This kind of exposure will result in color shifts, but will not show any physical changes to the material itself. Moisture and temperature are two other variables of outdoor testing that play a large role in the degradation of the materials, although sunlight is typically considered to be the worst. Seasonal variability will also have a large affect upon outdoor testing and can vary from year to year (Everett, 2001).

There are several different methods for mounting and exposure with outdoor testing. The exposure angle for an outdoor test is extremely important. A 90° angle is the most realistic angle for testing, but it results in exposure to reduced amounts of sunlight, lower temperatures, and fewer hours of wetness. A 45° angle is the most commonly used angle because it allows for more light exposure. A 5° angle is used to allow water to drain off of the test subject but to maintain a mostly flat exposure. The mountings used to hold the materials being tested are commonly frames or racks made out of either aluminum, stainless steel, or wood. They are designed to hold the material in place without damaging it. The mountings can be either open-backed or backed. The open-backing is used for rigid materials. A backed mounting is used for non-rigid materials, and the backing is most often made of plywood. This kind of backing causes the material to be exposed to a longer wet time and higher temperatures (Everett, 2001).

The direct exposure method involves mounting the material so that the front surface has no covering on it and faces the sun. This allows for the material to be exposed to all the elements of surrounding atmosphere. A material can also be covered by glass for a different exposure method. However, glass will filter out some of the sunlight spectrum and will cause less degradation due to light exposure for materials that are covered with glass. This type of testing is normally used for interior materials and not for outdoor testing (Everett, 2001).

Problems with Permanence Testing

One of the biggest issues with the testing of light stability in inkjet prints is reciprocity failure. This occurs when patches fade faster when exposed to a smaller amount of light instead of when exposed to a larger amount of light (Everett, 2002). This is an enormous problem when light-fastness is tested through the use of accelerated light-fastness testing. Accelerated light-fastness testing is used to obtain the data in a timetable that allows it to still be relevant. If the image suffers from reciprocity, then it will not show the same amount of fading under the accelerated light test as it does when exposed under normal conditions that are less severe. The fading will actually be worse under normal conditions than under the accelerated testing, making the findings from the light-fastness test erroneous (Vogt, 2001).

A problem with developing lifetime predictions is that a mathematical formula does not necessarily give an accurate prediction. There can be extenuating circumstances that were not included in the data set and, therefore, are not factored into the equation. Data generated by light stability testing will not necessarily show whether or not a certain combination of ink and substrate yields the most stable image. The data collected needs to be compared to data from numerous tests and numerous types of substrates to evaluate which combination might work best under determined conditions (Everett, 2002). Ideally, printers would look at the gathered data to determine which combination of paper and ink will give them the longest lasting print. Further research must be done on how to extrapolate data from laboratory tests into real-world environments, so that conclusions regarding longevity can be reached.

Another area that can cause problems during testing is the monitoring of percent relative humidity, percent ozone, and any other gases that can affect fading. These factors are not being monitored in this study because of the necessity of monitoring them in a controlled environment (Vogt, 2001). There is no method to monitor the gases in an uncontrolled environment without the use of equipment that far exceeds the budget for this study.

Substrates

A substrate is the material onto which an image is printed. There are different kinds of substrates, ranging from regular paper to synthetic substrates (Kipphan, 2001). Most inkjet substrates contain a coating which allows for the ink to better adhere to the surface of the paper or synthetic substrates, unless solvent-based inks are being used during printing. Specifically, most synthetic substrates are incapable of being printed on with water-based ink sets without a coating (Kipphan, 2001). Most of the synthetic substrates that are on the market today have a very similar look and feel of paper. They last longer and are more durable than paper, thus making them suitable for outdoor uses (Darwen, 2004).

The substrate surfaces can be described in one of two ways: either porous or non-porous. Porous substrates have voids or pores, which absorb ink into the substrate. This also allows for air to move through the coating and to expose the ink layer to different types of contaminants (Guo & Miller, 2001). Porous substrates are normally made from longer fibers. These substrates are often coated in order to reduce the problems caused by contaminants seeping into the paper and may have many fillers added in an attempt to fill in the gaps (Wilson, 1998). They are most commonly coated with silica or alumina with pores (Nishimura, 2006). Porous substrates can have issues with ink application; if the substrate is too porous, the ink may penetrate too deeply and be visible from the backside of the substrate. This excessive penetration of the ink can also cause too little ink to remain on the surface of the print, causing the print to appear lighter than necessary (Wilson, 1998).

Nonporous substrates, also known as swellable substrates tend to expand to absorb the ink, so that only a tiny layer of ink is exposed to air and direct light (Guo & Miller, 2001). They are generally made out of short fibers, which are compact and do not leave as many gaps in the surface. This type of substrate normally has three layers: a protective top layer, a layer that fixes the ink, and a layer that absorbs additional ink components (Print Permanence, Epson White Paper, 2005). One benefit of nonporous substrates is that they do not fade as quickly as porous substrates do (Guo & Miller, 2001). These substrates tend to be unaffected by atmospheric pollutants, helping with their resistance (Nishimura, 2006). However, nonporous substrates swell with exposure to moisture. If they are exposed to high humidity or to moisture, the substrate will swell, and the effect of the swelling may not be reversible, leaving the customer with a ruined print. The increased moisture content in these substrates can cause them to curl or to have dimensional changes, which will have a profound effect upon the appearance of the print. For substrates that are nonporous, it is best to make an effort to prevent them from coming into contact with moisture.

Vinyl

Scientist, Waldo Sermon, discovered vinyl during the 1920s. It was discovered accidentally while he was researching new ways to create synthetic adhesives. Vinyl is made out of a material called polyvinyl chloride (PVC). After its discovery, vinyl began to be used in multiple ways to create a large variety of products, such as raincoats, shower curtains, and others. Vinyl is currently the second largest selling plastic in the world and is made by converting hydrocarbon materials and chlorine into polymers through the process of polymerization. This process creates a fine resin powder, which is then converted into the end-product desired (Vinyl Institute, 2005).

Tyvek (DuPont)

Tyvek (Dupont) is a material created by the DuPont Company. It is a unique material that can be used as a fabric, paper, or synthetic film, but is actually none of these items (Darwen, 2004). Tyvek (Dupont) is made out of high-density polyethylene fibers called spunbonded olefin. It is created by taking the fibers, flash spinning them, laying them on as a web on a moving bed, and bonding them together through heat and pressure. No fillers, binders or sizers are used during the process. There are two different types of Tyvek (DuPont): hard and soft structure. The soft structure is very similar to a fabric and can be draped, or even worn as clothing. The hard structure resembles paper and often replaces paper where there is a need for a high tear resistance and a lighter weight (DuPont, What is Tyvek, 2005).

Tyvek (DuPont) was discovered in 1955 by Jim White when he observed polyethylene fluff accidentally coming out of a pipe. In 1965, it was engineered into a sheet structure; however, commercial production of Tyvek (DuPont) only started in 1967. It has many different uses: printing, envelopes, protective apparel, medical packaging, and covers. The most popular use of Tyvek (DuPont) is in construction (DuPont, 2005b).

Printing on Tyvek (Dupont) with liquid can contribute to its short lifespan. Certain solvents, adhesives, and coatings can cause the material to swell. This effect is reversible if the liquid evaporates, but if the solvent contained a binder or vehicle, the result is much more likely to be permanent. One way to prevent swelling from solvents is to dry the print in an oven in order for the solvent to evaporate quickly. Swelling can also be caused by some resins and low-weight adhesives. This type of swelling is permanent and can sometimes take several days or weeks after application before it becomes noticeable. Printers should test the solvents that they will use before printing with them on Tyvek (DuPont). Another issue with printing on Tyvek (Dupont) is that it absorbs little or no moisture. While this may have great benefits when creating outdoor signs, solvents can cause problems with drying times which need to be longer. If the Tyvek (Dupont) is uncoated, it will have a noticeable swirl pattern. The pattern will not be covered up by most inks, but it can be minimized with the use of multi-colored patterns or lighter colors (DuPont, 2005a).

Summary

The ability of an inkjet print to maintain its integrity and not fade requires different types of testing, which are used to examine the rate of fading. Rarely, if ever, is testing done outside of controlled environments or in the “real-world” to determine a rate of fading. This lack of “real-world” testing causes many problems to occur, such as reciprocity failure. The inkjet fading tests reviewed above are known industry standards of inkjet testing and encompass the many different areas of inkjet fading. This research encompasses all of these different areas, and the literature on those tests was used as a basis for the methodology of the experiment. The review of literature on the different inks and substrates has shown the researcher what may be expected from different substrates and why a specific ink set is important. The environmental regulations have a firm hold upon the printing industry and play a key role in the choice of ink sets for printing companies. This knowledge has led to the choice of an eco-solvent ink set for testing. Outdoor testing was chosen as a method to look at problems with inkjet fade testing because it does not involve the threat of reciprocity failure and will give a good example of why the current testing methods need to be re-evaluated.

Chapter 4

Problem Statement

The fading property of print on three different synthetic banner substrates — Economy Scrim Banner Blockout, Lightweight Banner Vinyl, and Tyvek Water Repellent Banner (DuPont) — when exposed to outdoor environmental variables — precipitation, uv index, temperature, pollution, and humidity— was examined for correlations between the change in color of either the base or the ink and the environmental variables the printed substrates were exposed to. A Roland SolJet Pro II V, with a six-color eco-solvent ink set, was selected as the print engine. A novel mutli-variant statistical approach was applied to the research in order to correlate the uncontrolled environmental factors and print fading. This was the first known study to learn how "real world" conditions impact print quality. This study will aid future researchers conducting accelerating testing to better understand which variables should be tested and which combinations of variables should be tested.

Chapter 5

Methodology

Overview

The three substrates tested were Economy Scrim Banner Blockout (code VSM-SBB), Tyvek (DuPont) Banner (code PCM-WTBM), and Lightweight Banner Vinyl (code ESM-LBV). The ink set that was used is the eco-sol (Roland) six-color ink set for the Roland SolJet Pro II V.

A test target page was printed on the Roland SolJet Pro II V and consisted of a set of 30 identical test targets of each color patch on each of the three different substrates. Two sets were made: one for environmental testing and one for dark storage testing. The prints were made in the Digital Publishing Center (DPC) at the Rochester Institute of Technology (RIT) and were allowed to dry for 24 hours on a table in the DPC. This was to ensure that the ink fully adhered to the substrate before testing began.

After the prints were allowed to dry for 24 hours in ambient room conditions on a table in the DPC, the test target patches were measured for density and CIELAB values before the exposure occurred. These values were labeled as Week 0. This was done using an X-Rite 530 spectrophotometer in the Color Management Systems (CMS) Lab at RIT.

Following the initial first measurement, the three prints were placed at a 90° angle in wooden frames on the roof of Building 7B at the RIT campus in Rochester, New York. The second set was laid, one on top of the other, in a 16x20 inch Print Lux Box that had a black lining and was made by the company, Archival Methods. The box was placed inside a drawer in the CMS lab.

The prints were placed in their respective conditions for seventeen weeks with initial measurements being Week 0 and the final week being Week 16. Every Monday evening, the dark storage prints were removed from the drawer, taken out of the box, and measured. After the measurements were taken, the prints were returned to the drawer until the following week. The set of prints on the roof were taken down from the roof every Tuesday morning. If the prints were wet due to weather conditions, they were allowed time to dry indoors before measuring.

The drying time was determined prior to the experiment by including an extra print on each substrate and measuring the density of the dry print, wetting the print, and then measuring the density every five minutes. The density readings were reviewed to see if the density was different when the print was wet from when it was dry and if so, after how much time the density returned to normal or stopped shifting. Thus, the prints were allowed to dry for approximately an hour, if they were wet as designated by the wetting test. This experiment has been designed to simulate real-world conditions for an outdoor advertising sign as closely as possible.

If there was snow on the prints when they were removed from the roof, the snow was shaken off, instead of brushed off, since brushing off the snow would cause undue wear and tear to the surface of the prints. The prints were removed from the frame and measured after they had been allowed to dry. After measuring, they were returned to the frame and taken back to the roof. Measurements were recorded weekly in this manner for 16 weeks.

▼ Weather Watch

	Tonight	Tomorrow
Maximum Humidity:	**66 %**	**67 %**
Wind Speed	**S** **7 mph**	**N** **11 mph**

Figure 2. Humidity and Wind Speed from www.weather.com

	Today	Tomorrow
UV Index:	**3 Moderate**	**2 Low**
Sunrise:	**6:47 AM**	**6:45 AM**
Sunset:	**6:00 PM**	**6:01 PM**
Daylight Remaining:	**2 hrs 44 min**	

Figure 3. UV Index and Daylight from www.weather.com

Yesterday hourly reports

	High	Low	Precip
Actuals	**25°F**	**5°F**	--
Averages	**37°F**	**20°F**	--
Records	**63°F** (1954)	**-2°F** (1993)	--

Figure 4. Temperature Ranges from www.weather.com

Excel was used to track the weather conditions over the sixteen weeks of the experiment. As shown in Figures 2, 3, and 4, weather information was obtained daily from www.weather.com under the Rochester area code of 14623. Information recorded included UV Index (average for the day), temperature (average low and high for the day), humidity (average for the day), and pollution levels. The data was then averaged for the week. This allowed for the rate of fading to be graphed, along with the weather variables. Once all of the data had been collected, a statistical analysis to eliminate irrelevant variables from the data set was conducted.

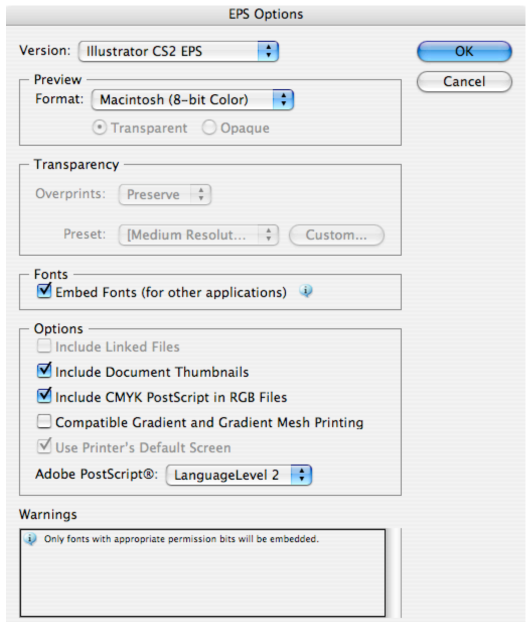

Figure 5. EPS Settings

Test Target

The test target was designed in Adobe Illustrator CS2 and saved as an EPS file. When the file was saved as an EPS, the color management was turned off (Figure 5). The test target consisted of nine patches: CMYK, RGB, and two grey patches. It contained an area with patches of pure cyan, magenta, yellow, and black. It also contained patches of mixed CMYK for the secondary color patches: blue, red, green, and the two patches of grey. The two patches of grey were created using CMY for one and CMYK for the other.

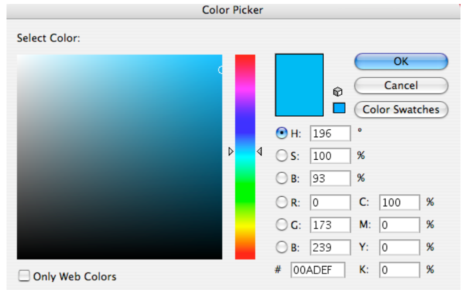

Figure 6. Cyan Color Settings

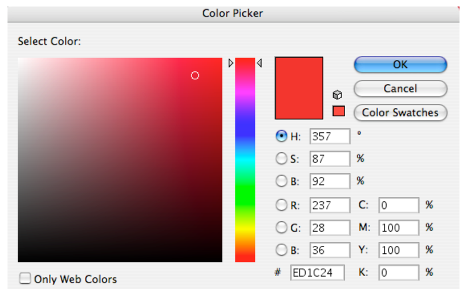

Figure 7. Red Color Settings

The patches of color were created in Adobe Illustrator CS2 by using the CMYK sliders. For pure CMYK patches, 100% was chosen for each color (Figure 6). For RGB, the combinations of the two colors that create the actual color were chosen; for example, 100% Y and 100% M for red (Figure 7). The file was then saved as an EPS file with the settings previously discussed (Figure 5).

Printing

The printing was conducted in the DPC on the Roland SolJet Pro II V using the Versa Works raster image processor (RIP). The inkjet printer was set to a heat setting of 50° Celsius, and a print quality setting of high quality and specific profile settings were selected for each substrate. The profiles came from the Roland DGA Corporation and were installed and updated with the software for the printer. The Light Weight Banner used a profile that was designed specifically for that substrate, the LBV profile. For Tyvek (Dupont), there was no specific profile available. A profile was selected that had the same first three letters in its code, which came from Roland DGA corporation, PCM, that was for matte coated, as Tyvek (Dupont) Banner has a matte coating on it. The Economy Scrim Banner Blockout also did not have a profile available; the profile used for it was the LBV profile the same as was used for the Light Weight Banner because it gave the least amount of banding. The prints were then allowed to dry for twenty-four hours on a table in the DPC underneath fluorescent lights and in ambient room humidity and temperature.

Measurement

The measurement process was done in the CMS lab at RIT. Before any measurements were taken by the researcher the spectrophotometer was calibrated. This was done at the beginning every time measurements of the samples were taken. The measurements were taken, using a program that allows the data to be directly imported into Excel, eliminating the need for hand entry. The same spectrophotometer from the X-Rite company (#1830) was used every time the measurements were taken, and the same settings (as shown in Figures 8 and 9) in the ToolCrib software were used to allow entry into Excel.

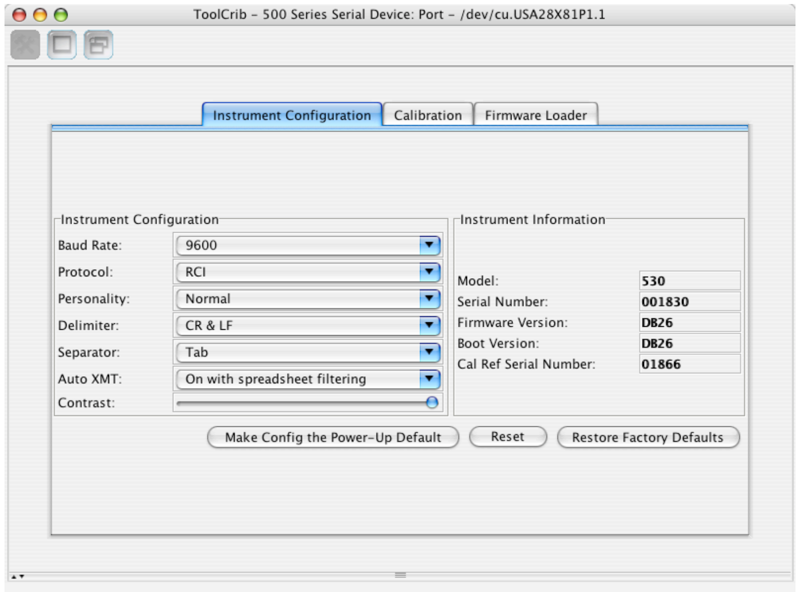

Figure 8. ToolCrib Software Settings

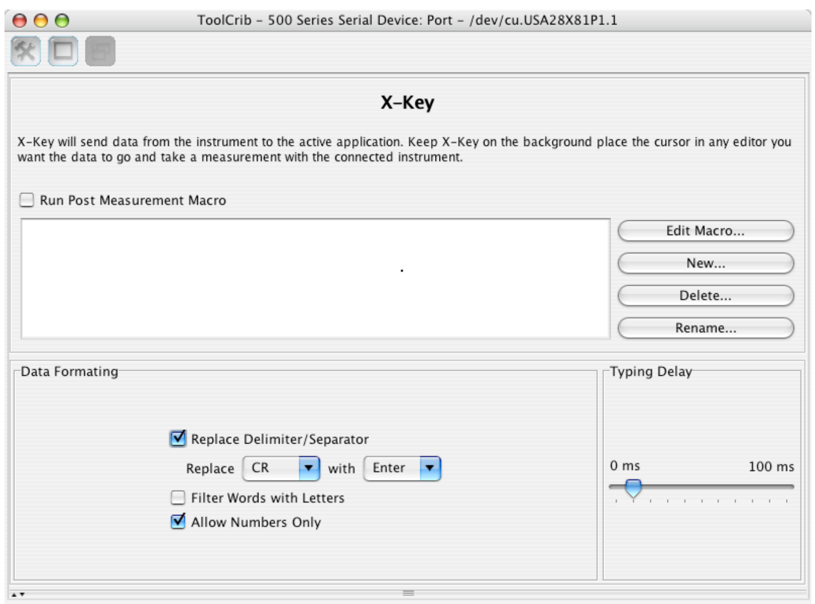

Figure 9. ToolCrib Software Settings

The ability of the spectrophotometer to repeat the measurements or the repeatability of the spectrophotometer was calculated with the GCA Lab-Ref™ (Serial

#300179). The spectrophotometer was then used to measure the Lab values of the known patches on the target five times. Using the known values for the patches as the reference value, the ΔE_{ab} was calculated for the measurements taken. The standard deviation was then calculated for each of the patches in each of the five measurements. The average of the standard deviation for all the patches for all five times was then calculated. The repeatability of the device was determined to be plus or minus 0.02.

Statistics

A multiple regression analysis was conducted to determine which weather variables affect fading. The data was separated by the ΔE_{ab} for each color patch of the test target. The environmental variable data was duplicated thirty times, in order to have as many environmental variable data points as there were ΔE_{ab} data points. Then a multiple regression analysis was conducted, one at a time, for each of the nine color patches (CMYKRGBGG) in the test target.

A regression was run with the data from all sixteen weeks between measured patch properties and the averaged weather variables for that week. The weather variable that has the highest p-value over 0.05 was removed from the data set for that color patch, and the regression run again. The next variable with the highest p-value over 0.05 was removed (and so on) until no more variables could be removed. The value 0.05 was used as the determining factor because a confidence level of 95% was chosen or an alpha of 0.05. The confidence level of 95% was chosen because it is an accepted “norm” by statisticians and is the confidence level most often used in studies similar to this one. This gave the researcher only a 5% margin of error and is the typical margin of error used by statisticians. The p-value is the probability of observing a test statistic as extreme as, or more extreme than, the one actually observed. After no more variables could be removed, a formula was produced from the data that could be used to predict fading rates for the substrate combinations tested.

Limitations

A limitation was that ΔE_{ab} is not uniformly distributed. It has no negative value causing a graph to be skewed in one direction. Due to this skewness a large amount of samples needed to be taken in order to ensure the data showed the true results of the experiment. Adding more time and cost to the experiment and limiting the ability of the research to add extra squares for density, etc.

Chapter 6

Results

Multiple Regression Analysis

Introduction

A multiple regression analysis of ΔE_{ab} versus the environmental variables (Precipitation, Low Temperature, High Temperature, Humidity, UV Index, and Pollution) was conducted for the cyan patch, magenta patch, blue patch, and substrate patch to determine which environmental variables affected the ΔE_{ab} for those patches. The pollution variable was removed from the multiple regression analysis because it did not vary over the entire seventeen week period (See Appendix A).

The purpose of the analysis was to find the variables, which correlated to the changes in ΔE_{ab}. However, this data analysis assumes a normal distribution of the ΔE_{ab} samples. ΔE_{ab} is not considered normally distributed because the equation used to calculate it does not allow for a negative value, thus the distribution will always be skewed to the right (Viggiano, 1999). In this case, it is reasonable to use these types of statistical methods, even for skewed data such as ΔE_{ab}, because color difference data is always skewed to larger color differences. This study uses statistical methods that assume normal distribution; studies involving ΔE_{ab} have been conducted previously that used this type of statistical method because the skewness of the distribution is always skewed to larger color differences (Viggiano, 1999). The following regression analysis is merely an example of what might be correlated to ΔE_{ab} for this experiment if the distribution were normal. The multiple regressions produce an equation that could be used to predict what ΔE_{ab} would be achieved with specific conditions and can be used to predict how a substrate might react to the same environmental variables as were tested. The model is not recommended for extrapolation, and the conditions entered into the equation cannot exceed those of the experiment.

Table 1. Results from a multiple regression analysis showing the correlation of ΔE_{ab} with the variables.

	R^2	Std. Error	Intercept	Time	Low Temp.	High Temp.	Humidity	Precip.	UV Index
ESM Substrate	0.8828	0.1679	0.3865	0.0951	-0.0107	0.0042	x	x	x
ESM Cyan	0.9006	0.2636	0.4441	0.1635	x	x	x	x	0.0776
ESM Magenta	0.7308	0.3737	1.4899	0.1528	0.0097	x	-1.2260	x	-0.2006
ESM Blue	0.7411	0.6130	1.0917	0.2346	x	x	x	x	-0.1062
VSM Substrate	0.6966	0.2374	0.7714	0.0855	-0.0155	0.0145	1.9484	x	-0.1122
VSM Cyan	0.9670	0.5129	3.1292	0.5935	0.0299	-0.0354	-1.4067	1.9044	0.1070
VSM Magenta	0.4356	0.3588	-1.2394	0.0660	x	0.0198	2.9252	x	x
VSM Blue	0.9043	0.5206	0.7693	0.3116	x	x	x	x	0.3209
PCM Substrate	0.4180	0.4309	1.6855	0.0734	-0.0383	0.0504	3.8733	-1.4361	-0.3739
PCM Cyan	0.8261	0.4008	2.3658	0.2199	-0.0203	0.0152	x	x	-0.4381
PCM Magenta	0.7451	0.3847	2.0656	0.1839	-0.0133	0.0230	x	x	-0.7196
PCM Blue	0.7565	0.4452	1.8736	0.2113	-0.0184	0.0153	x	x	-0.6331

Table 1 shows the results of the multiple regression analysis conducted with the ΔE_{ab} for the outdoor set of prints and the environmental variables that affected them, along with the amount of time that they were exposed to the environment. The variables that did not correlate for that color patch have an x instead of a coefficient in their columns. The cyan, magenta, blue, and substrate color patches were chosen for the regression analysis because they showed the highest rate of $\Delta E_{ab.}$

Time (in weeks) was the only variable which correlated with all of the color patches and for each substrate tested when a successful model was created. The ΔE_{ab} increased with time for all substrates, although it did not always increase in a linear fashion due to the affects of light and the environmental variables.

The first number in the table, R^2, reflects how much of the data actually fell into the correlation. The researcher had decided for the purpose of this study that any R^2 less than 0.85 would not be considered useful. This was decided on because 0.9 would have eliminated too many, and 0.80 would allow room for too much error.

The standard error is the amount of deviation of the coefficient from the correlation. A standard error higher than 0.30 will not be considered useful for the terms of this study. If the coefficient shows a large deviation, then the correlation will be unusable for prediction purposes.

ESM Substrate

The ESM substrate showed a correlation between ΔE_{ab} and time, low temperature, and high temperature. ΔE_{ab} was unaffected by the humidity, precipitation, and UV index. The R^2 for this analysis was 0.8828. The standard error for the regression is low, 0.1679, so it can be statistically assumed that this regression was a good representation of the variables that affected the substrate. The low temperature variable shows a negative coefficient (inversely proportional), meaning that a low temperature inversely affects the ΔE_{ab} or causes it to decrease as the temperature decreases. Thus the color is changing in the opposite direction in the color space when the temperature is colder from when it is warmer. For example if in warm weather the color has a negative b* it will have a positive b* in cold weather. This gives the illusion that the lower temperatures are causing a reversal of the earlier color shift. The high temperature has a positive coefficient, meaning it causes the ΔE_{ab} to increase as it increases. When using ESM for an outdoor advertising sign where a large amount of the substrate will be showing, or where it is important for the substrate to maintain its original appearance, it is best to avoid warm weather. The model of the rate of fading for the ESM substrate in order to forecast the ΔE_{ab} has the form as shown in Equation 1.

$$\text{y hat} = 0.3865 + (0.0951*\text{Week}) - (0.0107*\text{Low Temp.}) + (0.0042*\text{High Temp.}) \quad (1)$$

where week = time in weeks

where low temp. = average low temperature in Fahrenheit for the week

where high temp. = average high temperature in Fahrenheit for the week

The formula can be used to determine how the substrate would react in a particular climate, using the predicted temperature lows and highs for that climate. This will allow the consumer to be able to gauge approximately how long the sign will last based upon their specifications for when it will no longer be viewable in a manner befitting their needs.

ESM Cyan

The cyan patch on ESM showed a correlation to the time and UV index variables. The R^2 for this analysis was 0.9006, high enough to say that only 10% of the data did not fall into the correlation. The standard error was 0.2636, not high enough to discredit the analysis. All of the coefficients had a positive value, so they all cause the ΔE_{ab} to increase with increased exposure to either time or UV index. The model to predict the ΔE_{ab} at a specific amount of time and UV index would have the following form, as shown in Equation 2.

y hat = 0.4441 + (0.1635*Week) + (0.0776*UV Index) (2)

where week = time in weeks

where UV index = average of the UV index for the week

All of the same benefits of the model in Equation 1 would hold true for Equation 2.

Low R^2

The regression analysis for ESM magenta, ESM blue, VSM Substrate, VSM Magenta, PCM substrate, PCM Cyan, PCM magenta and PCM blue cannot be used to make any assumptions about which variables affect the $\Delta E_{ab,}$ and a model can not be created because the R^2 was too low.

High Standard Error

Both the cyan patch and the blue patch on VSM showed a high R^2, but the standard error for these patches were also higher then allowable. This standard error is above 0.30, and it can be assumed that a large amount of deviation from the correlation occurs in the coefficient. Due to the high amount of deviation in the coefficient from the correlation, the prediction model, which would be obtained from this data, was not a good indicator of which variables would affect the ΔE_{ab}.

Colorimetric Difference

Introduction

The following data analysis and graphs are a representation of the change in color from the reference value (which was measured in Week 0) that was calculated for each of the thirty patches for that color patch and then averaged for that week. This change in color was the ΔE_{ab} calculated for each of the color patches (CMYKRGBGG), with the reference value being the L*a*b* measurements taken 24 hours after printing while the prints were stored in a temperature controlled room.

ΔE_{ab} of Substrate Patch

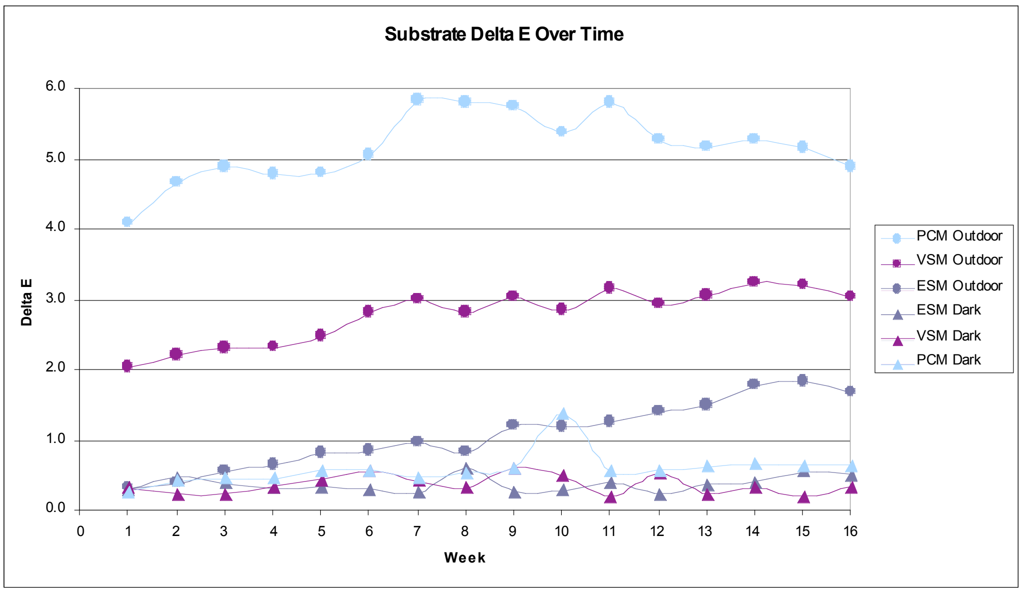

Figure 10. ΔE_{ab} of the substrate patch as a function of time for the dark storage set and outdoor set of prints for all three substrates

Figure 10 shows the change in color of the measured substrate patch for both the dark storage and outdoor set of prints on all three substrates. The fluctuations in ΔE_{ab} on the PCM outdoor substrate may be associated with the appearance and subsequent disappearance of mold on that substrate. The VSM and PCM outdoor substrate show a larger shift in color than the ESM outdoor substrate.

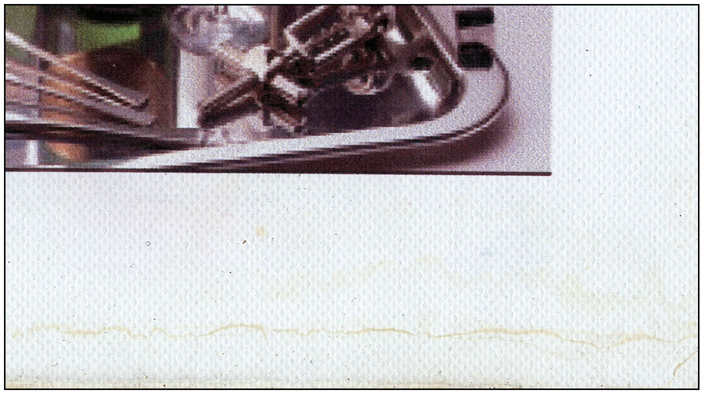

Figure 11. Scanned Image of the water stain on the bottom of the photograph set on the VSM substrate

This larger shift in color may be explained by the difference between the uncoated ESM and the two matte coated substrates, VSM and PCM. Moisture had different effects on the matte coatings then on the uncoated vinyl (ESM). The visual analysis noted that the matte coatings on the VSM and PCM substrates absorbed water. The absorption level for the two substrates was different. PCM would absorb water until it was all the way through to the backside whereas VSM would not absorb as much water. The water absorbed into these two substrates left visible stains on the substrates unprinted areas as seen in figure 11 and 12. The absorption of water was then multiplied by the wooden backing used for the frames, which soaked in water causing the substrates to stay wet longer.

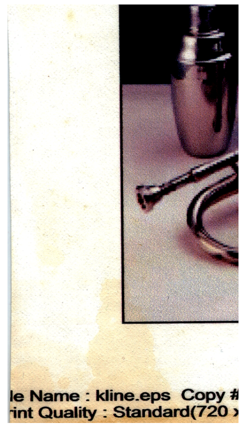

Figure 12. Scanned Image of the stain on the lower left corner of the outdoor photograph set on the PCM substrate

ΔE_{ab} of the RGB Patches on All Substrates

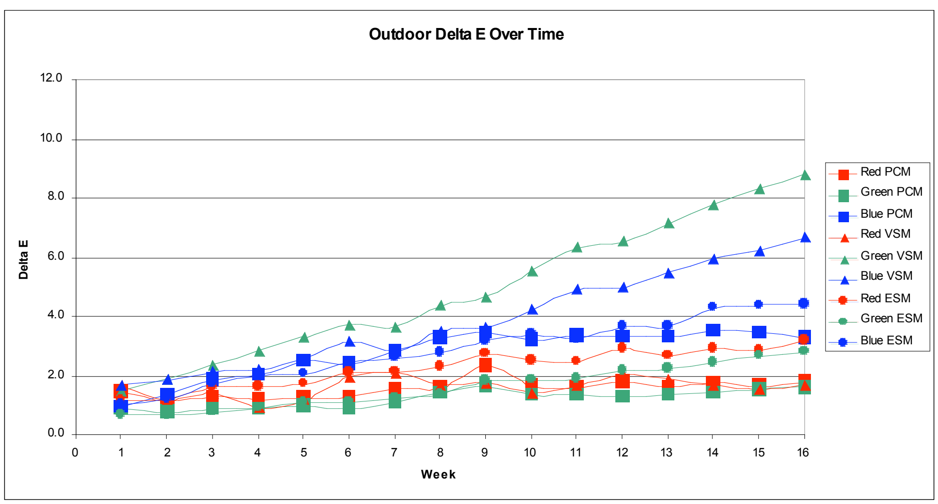

Figure 13. ΔE_{ab} of the RGB patches as a function of time for all three of the substrates

Figure 13 shows that the PCM substrate appears to be the most stable substrate for the overprint or RGB colors. VSM has the highest rate of ΔE_{ab} in the overprint patches of all three substrates for both outdoor and dark storage. The ESM and PCM substrate appear to be more stable substrates for mixed colors than the VSM substrate.

The order in which the inks are put down onto the substrates may be affecting the fading in the mixed color patches. If cyan (which was found to be the unstable ink in VSM) is put down last or on top, then that color patch will change at a similar rate to cyan. This effect is known as the "shielding effect" in the industry and refers to the top-most ink absorbing wavelengths of light, thus shielding the lower or earlier laid down inks from it (Nishimura, 2006).

ΔE_{ab} of Gray Patches on the PCM Substrate

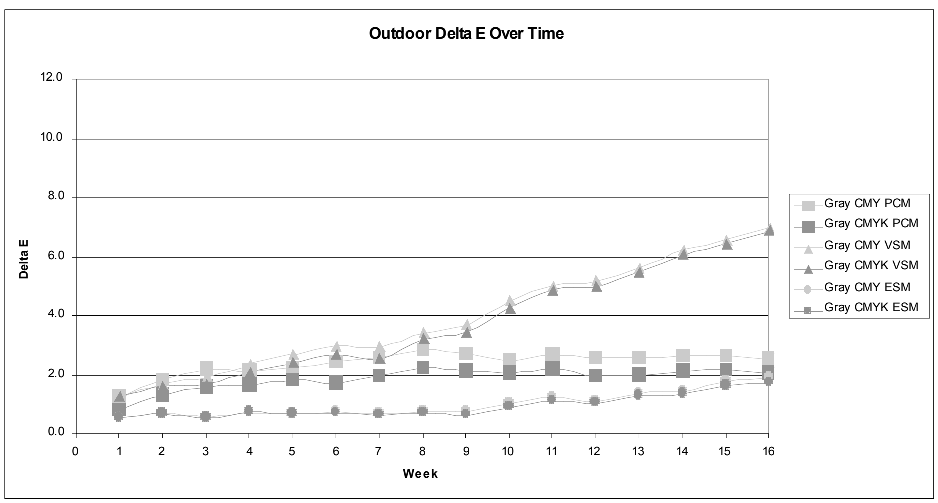

Figure 14. ΔE_{ab} of the two gray patches as a function of time for all three of the substrates

The patch of gray in the outdoor set that does not have black ink on it faded at a slightly higher rate than did the patch of gray containing black ink as seen in figure 14. This is because black ink is typically a more stable ink than the other three inks (CMY), and the gray patch with black ink will be more stable. Additionally, printing with four inks, instead of three, results in higher pigment coverage, and one or two constituent inks will not have as large an effect on the overall color, as measured by a spectrodensitometer.

The ESM prints that were stored in the dark showed a visible shift in the gray color patches to magenta after the fifth week. The rest of the color patches did not show a visible change in color. This substrate was the only substrate that had a visible change in the dark storage set of prints. However, the magenta shift was not large enough to be measured because the gray for ESM never shows a ΔE higher then 2.0.

Density

The figure 14 shows the results of the density measurements on the ESM outdoor substrate taken over seventeen weeks, with the first set of measurements taken 24 hours after the prints were created, or at Week 0. Thirty patches of the same color were measured, and the averages of those thirty were used as a representation for the density of that week. The filters used for measuring the density of each of the different color patches were:

- Cyan – C
- Magenta – M
- Yellow – Y
- Black – V
- Red – M

- Green – C
- Blue – C
- Gray CMY
- CMYK – V
- Paper – V

The same filters were used for each of the three substrates. The filters for the overprints were chosen, based on the filter that showed the highest density reading in the initial week, Week 0.

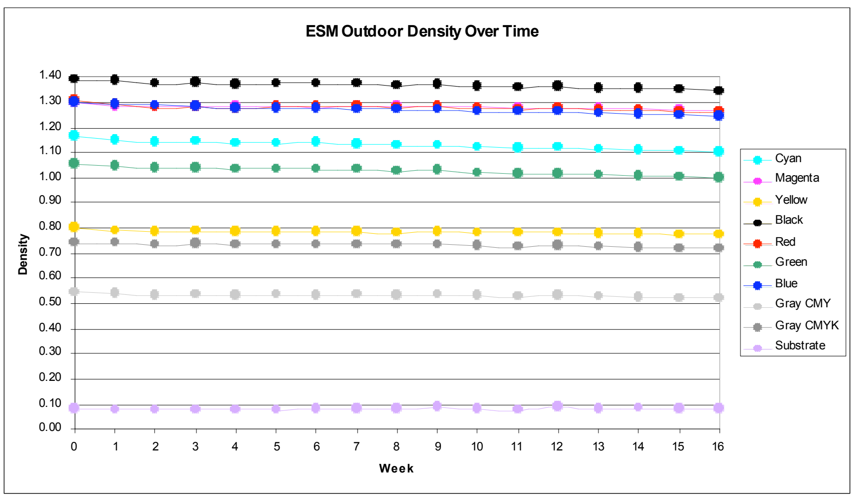

Figure 15. Density as a function of time for the ESM substrate outdoor set of prints

Figure 15 is representative of the density graphs for all three substrates for the outdoor and dark storage sets of the prints. It can be concluded that none of the combinations of substrate and ink show a significant loss of density over time, despite a visible change in ΔE_{ab}. This change in density was not enough to meet the end point requirements (a 10% drop), however the changes in ΔE_{ab} were enough to meet the end points per the discussion in the section on Theoretical Basis for Study: Endpoints.

The density was found to be essentially invariant with time for each of the substrates, regardless of whether the substrate was exposed to the environmental variables or kept in a box with little to no light exposure. The lack of a density change may be attributed to patches of color all being one hundred percent patches and none of them being lower percentages. If a step wedge of each color had been included then a change in density may have been able to be recorded. Time and supplies would not allow for such an inclusion in this research and the change in color was deemed a more critical aspect of this study. The fact that the density does not change but there is a clear shift in the ΔE, as evidenced in the previous sections, means that the substrate (also known as the base) is changing with exposure to the environmental variables but the ink is not changing. This is supported by the lack of a change in density but a clear shift in color. If pigments are not disappearing then what is causing the color shift, the change in the base.

Chapter 7

Summary and Conclusions

Summary

Fading properties of print on three different synthetic substrates printed with eco-solvent inkjet when exposed to real-world outdoor environmental variables were examined. The experiment was designed to simulate real-world usage of an outdoor advertising sign, as closely as possible, given the research conditions. The experiment was used to compare ΔE_{ab} as a function of time, along with several environmental variables (UV index, humidity, low and high temperature, precipitation, and pollution). A statistical analysis was then conducted of the data that was collected, along with a visual analysis of the experiment throughout its entirety.

Multiple Regression Analysis

The regression analysis was useful in creating a prediction model for two of the color patches, ESM substrate and ESM cyan. The rest of the regression analysis for the other color patches was discarded, due to either a low R^2 or a high standard error. However, the prediction models that were able to be created can be used as a starting point for future research on the environmental variables that affect these types of substrates. They provide information to consumers on what types of materials to avoid in specific conditions and what behaviors may be expected from the materials when exposed to specific environmental variables. This study demonstrated a methodology to both measure and to analyze data regarding real-world permanence testing. It provided insight into how print on three different substrates interacted with environmental variables.

The multiple regression analysis technique can be used in real-world permanence testing. The multiple regression analysis created a prediction model for two color patches on the ESM substrate but the use of this prediction model is limited. The data that is entered into the model to create a prediction cannot exceed the data that was used to create the model. An example of data that would be within the limits of this study would be a sign that was going to be displayed during the winter months in Rochester. An example of a sign that was going to be displayed which would not be allowed to use these prediction models would be one that is to be displayed during the summer months in Rochester. Due to this limitation of the prediction model it should be used more as a suggestion as to which variables will affect the fading of the print but not as an absolute.

The multiple regression analysis worked for two of the color patches: ESM substrate and ESM cyan. It proved that the ESM substrate is influenced by three variables (time, high temperature, and low temperature), although the influence of the low temperature was in the opposite direction in the color space than high temperature or time or showed an inverse relationship. The ESM cyan proved to be influenced by only two variables (time and UV index), both in a positive manner.

These influences of the environmental variables on the ESM substrate have a profound impact when deciding upon whether or not to use this substrate. A consumer can make an approximation about the rate of fading based upon the prediction model to gain an idea about how the material would behave in a specific climate. This allows for a company creating outdoor signs to make better recommendations to clients and to have more knowledge about guaranteeing their work. The prediction model should be used as a guide for deciding upon which type of substrate to use with the knowledge of what environmental variables the sign will be facing for the duration of its use.

The prediction model can give a consumer an idea about how long before they can expect to replace it and how to choose the material best suited for what they are going to be using it for. For example, if a client went to a sign shop that used a large format Roland SolJet Pro II V and asked for a recommendation on what type of material their sign should be printed on. The printer could then obtain some more information about where it was going to be displayed. They would find out that the sign is going to be hung during soccer tournaments for a team's banner. It is going to be exposed to a high temperature of 90 degrees Fahrenheit, a low temperature of 32 degrees Fahrenheit, and an average UV index of 1.5 for 10 weeks. He or she would recommend ESM because the high and low temperatures will counteract each other and could tell the client to expect a change in substrate of ΔE_{ab} 1.3731 and a change in the cyan ink of ΔE_{ab} 2.1955. Thus the client will be prepared for a possible slight shift in the cyan ink but that it will be barely noticeable.

Unstable Ink

The cyan ink was the least stable ink on the VSM and PCM substrates out of the three substrates. The ESM cyan and magenta faded at about equal rates, which were higher than the other inks (yellow and black) on the ESM substrate. Cyan had a much larger ΔE_{ab} on the substrates and clearly stands out in the trend analysis as the least stable ink.

ESM Substrate

The most durable substrate was the ESM substrate. It showed the least amount of fading, both under exposure to the environmental variables and the dark storage set. The other two substrates both suffered from yellowing of the substrate and had a large ΔE_{ab} in the majority of their color patches. Therefore, if an advertising agency wished to create a sign that would last the longest in the environmental variables, the ESM material would be the best choice during a winter climate either in Rochester or in a location with a similar climate.

Coatings

The data obtained in this study shows that the coating of the substrate seemed to play a large role in how a substrate is affected by the environmental variables. The coated substrates (VSM and PCM) yellowed, while the substrate with no coating (ESM) did not yellow and the color patches were the most resistant; overall, the ESM was determined to be the most resistant to the environmental variables. This study yielded the recommendation that, if an outdoor sign is going to be created on a substrate with a matte coating, the advertiser should hang the sign in a manner in which it will be exposed to the least amount of moisture and humidity, in order to prevent the yellowing of the substrate.

Recommendations for Further Investigations

A researcher wishing to produce further research in this area of permanence pertaining to real-world exposure experiments has several choices. Research can be conducted into the coatings of synthetic materials. The coated materials displayed several problems with moisture; a study of the same material, both coated and uncoated, to see if the experiment would allow for a better understanding into the affect of the coatings.

Different exposure methods and different mounting methods could be used for holding the materials being tested to see if the mountings affected the results. This would allow for information to be collected about the affect of moisture between the mountings and the materials being tested, as well as for damage done to the materials by the mountings.

Conducting this same experiment for a longer period of time would shed light on several areas of concern raised by this experiment. The longer exposure time would provide better information about the reactions between the environmental variables and the materials. Information gathered over a longer period of time may allow the multiple regression analysis method to be used more effectively with the data.

The data that was collected from this experiment could be further analyzed, both statistically and non-statistically. A non-parametrical statistical method could be used to explore potential correlations between the environmental variables and the ΔE_{ab}. This would eliminate the restrictions of a non-normal distribution of ΔE_{ab}. Further methods for correlating the environmental variables with the changes in ΔE_{ab} could be explored.

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Appendix

Appendix A

Date	Precip Type	Precip	Pollution	Low Temp	Hi Temp	Max Humidity	UV Index
11/15/2005	Rain	0.07	Good	41.00	64.00	0.73	2.00
11/16/2005	sunny	0.00	Good	30.00	35.00	0.73	2.00
11/17/2005	Flurries/Rain	0.00	Good	26.00	33.00	0.83	2.00
11/18/2005	Flurries	0.00	Good	26.00	33.00	0.69	2.00
11/19/2005	partly cloudy	0.00	Good	33.00	46.00	0.50	2.00
11/20/2005	partly cloudy	0.00	Good	36.00	54.00	0.54	2.00
11/21/2005	cloudy	0.00	Moderate	39.00	51.00	0.82	2.00
11/22/2005	cloudy	0.05	Good	21.00	41.00	0.60	1.00
11/23/2005	mostly cloudy	0.00	Good	17.00	34.00	0.47	1.00
11/24/2005	snow	0.03	Good	15.00	34.00	0.64	2.00
11/25/2005	cloudy	0.00	Good	18.00	30.00	0.60	2.00
11/26/2005	snow	0.03	Good	23.00	31.00	0.60	2.00
11/27/2005	snow	0.06	Good	19.00	49.00	0.62	2.00
11/28/2005	mostly cloudy	0.11	Good	44.00	67.00	0.67	1.00
11/29/2005	rain	1.04	Moderate	42.00	67.00	0.90	1.00
11/30/2005	cloudy	0.00	Good	34.00	43.00	0.74	2.00
12/1/2005	snow	0.01	Good	33.00	35.00	0.70	1.00
12/2/2005	snow	0.01	Good	25.00	34.00	0.65	1.00
12/3/2005	cloudy	0.00	Good	23.00	30.00	0.66	1.00
12/4/2005	cloudy	0.05	Good	24.00	32.00	0.66	1.00

12/5/2005	cloudy	0.00	Good	23.00	29.00	0.66	1.00
12/6/2005	mostly cloudy	0.00	Good	17.00	27.00	0.61	1.00
12/7/2005	cloudy/snow	0.01	Good	17.00	26.00	0.63	1.00
12/8/2005	sunny	0.05	Good	11.00	28.00	0.66	1.00
12/9/2005	snow	0.07	Good	25.00	33.00	0.68	1.00
12/10/2005	sunny	0.00	Good	27.00	32.00	0.65	1.00
12/11/2005	light snow	0.01	Good	13.00	28.00	0.68	1.00
12/12/2005	cloudy	0.00	Good	28.00	33.00	0.69	1.00
12/13/2005	partly cloudy	0.00	Good	7.00	24.00	0.58	1.00
12/14/2005	cloudy	0.00	Moderate	2.00	21.00	0.46	1.00
12/15/2005	rain/snow	0.34	Good	14.00	32.00	0.66	1.00
12/16/2005	snow	0.19	Good	28.00	37.00	0.64	1.00
12/17/2005	cloudy	0.00	Good	22.00	26.00	0.65	1.00
12/18/2005	flurries/cloudy	0.00	Good	18.00	26.00	0.60	1.00
12/19/2005	partly cloudy	0.01	Good	20.00	26.00	0.60	1.00
12/20/2005	snow	0.01	Good	14.00	28.00	0.76	0.00
12/21/2005	flurries	0.00	Good	27.00	37.00	0.70	1.00
12/22/2005	flurries	0.07	Good	34.00	41.00	0.67	1.00
12/23/2005	cloudy	0.01	Moderate	35.00	42.00	0.77	1.00
12/24/2005	snow	0.11	Moderate	31.00	43.00	0.80	1.00
12/25/2005	cloudy	0.07	Moderate	32.00	37.00	0.70	1.00
12/26/2005	flurries/cloudy	0.07	Good	32.00	37.00	0.67	1.00
12/27/2005	cloudy	0.09	Good	28.00	44.00	0.69	1.00
12/28/2005	showers	0.01	Moderate	33.00	43.00	0.82	1.00
12/29/2005	light drizzle	0.00	Moderate	28.00	34.00	0.85	1.00

12/30/2005	cloudy	0.00	Good	28.00	34.00	0.72	1.00
12/31/2005	snow	0.02	Good	24.00	34.00	0.74	1.00
1/1/2006	cloudy	0.01	Good	29.00	36.00	0.80	1.00
1/2/2006	rain	0.07	Moderate	34.00	38.00	0.82	1.00
1/3/2006	cloudy	0.01	Good	36.00	39.00	0.84	1.00
1/4/2006	rain	0.07	Good	31.00	43.00	0.82	1.00
1/5/2006	cloudy	0.05	Good	32.00	42.00	0.76	1.00
1/6/2006	snow	0.02	Good	20.00	32.00	0.68	0.00
1/7/2006	cloudy/snow	0.02	Good	17.00	32.00	0.62	1.00
1/8/2006	cloudy	0.00	Good	31.00	40.00	0.73	1.00
1/9/2006	cloudy	0.00	Good	36.00	48.00	0.76	1.00
1/10/2006	partly cloudy	0.00	Good	32.00	41.00	0.65	1.00
1/11/2006	rain	0.31	Good	36.00	59.00	0.64	1.00
1/12/2006	cloudy	0.00	Good	35.00	54.00	0.63	1.00
1/13/2006	drizzle	0.00	Good	39.00	63.00	0.66	1.00
1/14/2006	rain/snow	0.57	Good	20.00	52.00	0.64	1.00
1/15/2006	mostly cloudy	0.00	Good	12.00	21.00	0.62	0.00
1/16/2006	sunny	0.00	Good	8.00	21.00	0.59	2.00
1/17/2006	rain	0.16	Moderate	16.00	43.00	0.68	1.00
1/18/2006	snow	0.07	Good	29.00	47.00	0.69	1.00
1/19/2006	partly cloudy	0.00	Good	29.00	46.00	0.60	1.00
1/20/2006	cloudy	0.00	Good	41.00	56.00	0.65	1.00
1/21/2006	cloudy	0.00	Good	25.00	40.00	0.64	1.00
1/22/2006	sunny	0.00	Good	32.00	40.00	0.61	2.00
1/23/2006	sunny	0.03	Good	27.00	44.00	0.67	1.00

1/24/2006	sunny/snow	0.01	Good	22.00	38.00	0.62	1.00
1/25/2006	snow	0.01	Good	15.00	23.00	0.75	1.00
1/26/2006	sunny	0.00	Good	12.00	21.00	0.65	2.00
1/27/2006	sunny	0.00	Moderate	11.00	41.00	0.54	2.00
1/28/2006	sunny	0.00	Moderate	35.00	50.00	0.80	2.00
1/29/2006	rain	0.53	Good	38.00	51.00	0.77	2.00
1/30/2006	cloudy	0.00	Good	38.00	54.00	0.72	1.00
1/31/2006	cloudy	0.00	Good	33.00	41.00	0.75	1.00
2/1/2006	cloudy	0.00	Good	29.00	38.00	0.70	1.00
2/2/2006	sunny	0.09	Good	37.00	54.00	0.70	1.00
2/3/2006	cloudy	0.51	Good	32.00	46.00	0.76	2.00
2/4/2006	sunny/showers	0.01	Good	27.00	45.00	0.79	2.00
2/5/2006	cloudy/snow	0.01	Good	27.00	45.00	0.65	1.00
2/6/2006	cloudy/snow	0.01	Good	25.00	31.00	0.62	2.00
2/7/2006	snow/sunny	0.01	Good	24.00	28.00	0.67	1.00
2/8/2006	cloudy/sunny	0.01	Good	16.00	25.00	0.69	2.00
2/9/2006	sunny/light snow	0.00	Good	10.00	26.00	0.77	2.00
2/10/2006	snow	0.07	Good	17.00	24.00	0.76	1.00
2/11/2006	sunny	0.00	Good	16.00	32.00	0.77	2.00
2/12/2006	partly cloudy	0.00	Good	15.00	27.00	0.67	2.00
2/13/2006	cloudy/snow	0.01	Good	16.00	31.00	0.65	2.00
2/14/2006	snow/cloudy	0.04	Moderate	26.00	39.00	0.71	2.00
2/15/2006	cloudy	0.00	Good	33.00	50.00	0.82	2.00
2/16/2006	showers	0.01	Moderate	24.00	60.00	0.70	3.00

2/17/2006	showers/snow	0.00	Good	12.00	27.00	0.61	2.00
2/18/2006	light snow	0.00	Good	12.00	27.00	0.60	3.00
2/19/2006	snow	0.00	Good	9.00	22.00	0.49	3.00
2/20/2006	cloudy	0.00	Good	14.00	28.00	0.60	2.00
2/21/2006	snow/cloudy	0.01	Good	22.00	34.00	0.65	3.00
2/22/2006	cloudy	0.00	Good	18.00	46.00	0.68	3.00
2/23/2006	cloudy	0.16	Moderate	29.00	41.00	0.64	3.00
2/24/2006	cloudy	0.00	Good	22.00	31.00	0.51	3.00
2/25/2006	snow	0.03	Good	21.00	43.00	0.63	3.00
2/26/2006	sunny/snow	0.01	Good	14.00	21.00	0.54	3.00
2/27/2006	sunny	0.03	Good	6.00	26.00	0.50	3.00
2/28/2006	sunny/snow	0.00	Good	5.00	25.00	0.59	3.00
3/1/2006	cloudy	0.00	Good	19.00	20.00	0.69	3.00
3/2/2006	cloudy	0.00	Good	18.00	29.00	0.66	3.00
3/3/2006	cloudy	0.00	Good	17.00	27.00	0.50	3.00
3/4/2006	sunny	0.00	Good	23.00	37.00	0.56	3.00
3/5/2006	sunny	0.00	Good	22.00	40.00	0.55	3.00
3/6/2006	sunny/cloudy	0.00	Good	20.00	35.00	0.64	3.00
3/7/2006	sunny	0.00	Good	22.00	33.00	0.66	4.00

Week 1							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	31.50	44.63	0.68	1.88	cloudy
Week 2							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.18	Good	25.43	44.57	0.64	1.57	snow
Week 3							

Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.01	Good	25.57	32.86	0.67	1.14	cloudy
Week 4							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	18.29	29.14	0.65	1.00	cloudy
Week 5							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.08	Good	16.86	28.00	0.62	0.86	cloudy/snow
Week 6							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.06	Good	31.29	40.14	0.71	1.00	flurries
Week 7							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	30.29	36.86	0.80	1.00	cloudy/rain
Week 8							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	28.43	39.71	0.72	0.86	cloudy
Week 9							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.15	Good	23.71	44.71	0.64	1.00	rain
Week 10							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	29.29	44.43	0.64	1.14	cloudy
Week 11							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.08	Good	26.00	40.14	0.71	1.57	sunny
Week 12							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.09	Good	28.71	41.00	0.70	1.43	cloudy
Week 13							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.02	Good	16.57	29.14	0.72	1.86	cloudy
Week 14							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.00	Good	18.00	35.43	0.64	2.57	snow
Week 15							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather

							Type
	0.03	Good	16.43	33.29	0.58	3.00	cloudy
Week 16							
Averages	Precip	Pollution	Low	Hi	Humidity	UV	Weather Type
	0.00	Good	20.14	31.57	0.61	3.14	sunny

Appendix B

Figure 16. Image of one of the prints hanging on the roof

Figure 17. Image of several of the prints on the roof

Figure 18. Image of how the wooden frames were held together

Figure 19. Image of archival box in dark storage

Figure 20. Image of measurement set up

Appendix C

Figure 21. Three Musicians Photograph used as part of test target

Figure 22. Metal Objects Photograph uses as part of test target

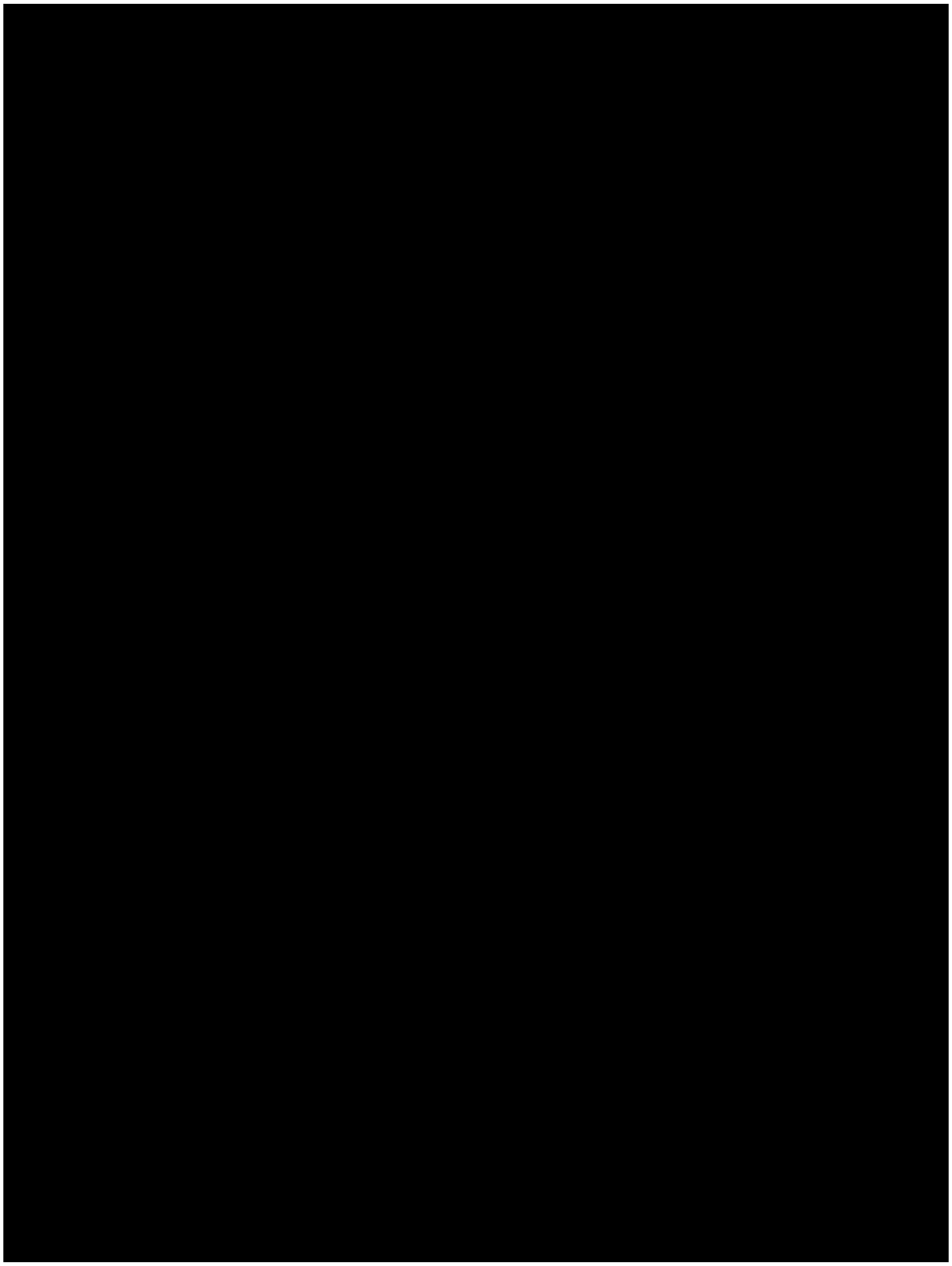

Figure 23. Smaller version of color patches for test target

Appendix D – Spectrodensitometer Repeatability

February 28, 2006															
Time: 4:51pm															
	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	90.24	-0.26	3.62	3.63	94.11	-0.46	0.04	0.22	0.51	0.35
black	13.10	0.60	0.60	0.85	45.00	13.32	0.98	1.02	1.41	46.15	0.22	0.38	0.42	0.61	0.68
cyan	58.20	-37.00	-41.70	55.75	228.42	58.23	-36.80	-41.47	55.44	228.41	0.03	0.20	0.23	0.31	0.09
magenta	48.70	72.20	0.30	72.20	0.24	49.27	72.29	-0.28	72.29	359.78	0.57	0.09	-0.58	0.82	0.62
yellow	86.70	-6.90	96.20	96.45	94.10	87.49	-6.99	95.91	96.16	94.17	0.79	-0.09	-0.29	0.85	0.51
gray	50.40	1.60	4.10	4.40	68.68	50.50	1.79	4.16	4.53	66.72	0.10	0.19	0.06	0.22	0.28
red	49.10	64.50	48.40	80.64	36.88	49.18	64.17	48.44	80.40	37.05	0.08	-0.33	0.04	0.34	0.15
green	53.00	-62.90	36.60	72.77	149.81	53.34	-62.55	36.49	72.42	149.74	0.34	0.35	-0.11	0.50	0.34
blue	25.80	21.80	-42.30	47.59	297.27	26.11	22.00	-42.29	47.67	297.48	0.31	0.20	0.01	0.37	0.26
brown	37.70	18.90	17.70	25.89	43.12	38.34	19.23	17.68	26.12	42.60	0.64	0.33	-0.02	0.72	0.59
purple	38.20	31.70	-15.10	35.11	334.53	38.57	32.00	-15.02	35.35	334.86	0.37	0.30	0.08	0.48	0.35
pastel	63.10	29.30	25.00	38.52	40.47	63.24	28.93	24.79	38.10	40.59	0.14	-0.37	-0.21	0.45	0.20
										Aver.	0.26	0.11	-0.01	0.51	0.37
										St. Dev.	0.33	0.25	0.26	0.20	0.19
	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	90.39	-0.19	3.64	3.64	92.99	-0.31	0.11	0.24	0.41	0.33
black	13.10	0.60	0.60	0.85	45.00	13.81	1.00	0.99	1.41	44.71	0.71	0.40	0.39	0.90	0.81
cyan	58.20	-37.00	-41.70	55.75	228.42	58.36	-36.88	-41.57	55.57	228.42	0.16	0.12	0.13	0.24	0.15
magenta	48.70	72.20	0.30	72.20	0.24	49.36	72.22	-0.42	72.22	359.67	0.66	0.02	-0.72	0.98	0.72
yellow	86.70	-6.90	96.20	96.45	94.10	87.65	-7.05	96.11	96.37	94.20	0.95	-0.15	-0.09	0.97	0.62
gray	50.40	1.60	4.10	4.40	68.68	50.71	1.75	4.21	4.56	67.43	0.31	0.15	0.11	0.36	0.38
red	49.10	64.50	48.40	80.64	36.88	49.40	64.35	48.31	80.47	36.90	0.30	-0.15	-0.09	0.35	0.30
green	53.00	-62.90	36.60	72.77	149.81	53.61	-62.86	36.45	72.66	149.89	0.61	0.04	-0.15	0.63	0.59
blue	25.80	21.80	-42.30	47.59	297.27	26.25	21.85	-42.15	47.48	297.40	0.45	0.05	0.15	0.48	0.35
brown	37.70	18.90	17.70	25.89	43.12	38.35	19.33	17.31	25.95	41.84	0.65	0.43	-0.39	0.87	0.73
purple	38.20	31.70	-15.10	35.11	334.53	38.47	31.75	-14.99	35.11	334.73	0.27	0.05	0.11	0.30	0.24
pastel	63.10	29.30	25.00	38.52	40.47	63.45	29.25	25.04	38.50	40.57	0.35	-0.05	0.04	0.36	0.30
										Aver.	0.43	0.08	-0.02	0.57	0.46
										St. Dev.	0.33	0.18	0.30	0.28	0.22
	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	90.26	-0.21	3.62	3.63	93.32	-0.44	0.09	0.22	0.50	0.36
black	13.10	0.60	0.60	0.85	45.00	13.53	0.97	1.03	1.41	46.72	0.43	0.37	0.43	0.71	0.72
cyan	58.20	-37.00	-41.70	55.75	228.42	58.21	-37.00	-41.71	55.76	228.42	0.01	0.00	-0.01	0.01	0.01
magenta	48.70	72.20	0.30	72.20	0.24	49.31	72.12	-0.38	72.12	359.70	0.61	-0.08	-0.68	0.92	0.67
yellow	86.70	-6.90	96.20	96.45	94.10	87.82	-7.10	96.28	96.54	94.22	1.12	-0.20	0.08	1.14	0.73
gray	50.40	1.60	4.10	4.40	68.68	50.74	1.74	4.14	4.49	67.20	0.34	0.14	0.04	0.37	0.39
red	49.10	64.50	48.40	80.64	36.88	49.39	64.38	48.07	80.35	36.75	0.29	-0.12	-0.33	0.46	0.31
green	53.00	-62.90	36.60	72.77	149.81	53.67	-63.18	36.66	73.05	149.88	0.67	-0.28	0.06	0.73	0.65
blue	25.80	21.80	-42.30	47.59	297.27	26.28	21.87	-42.27	47.59	297.36	0.48	0.07	0.03	0.49	0.36
brown	37.70	18.90	17.70	25.89	43.12	38.28	19.18	17.69	26.09	42.69	0.58	0.28	-0.01	0.64	0.53
purple	38.20	31.70	-15.10	35.11	334.53	38.53	31.90	-15.06	35.28	334.73	0.33	0.20	0.04	0.39	0.30
pastel	63.10	29.30	25.00	38.52	40.47	63.42	29.27	24.84	38.39	40.32	0.32	-0.03	-0.16	0.36	0.28
										Aver.	0.39	0.04	-0.02	0.56	0.44
										St. Dev.	0.38	0.19	0.28	0.29	0.22
	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	90.15	-0.21	3.59	3.60	93.35	-0.55	0.09	0.19	0.59	0.40
black	13.10	0.60	0.60	0.85	45.00	13.37	1.02	1.10	1.50	47.16	0.27	0.42	0.50	0.71	0.77
cyan	58.20	-37.00	-41.70	55.75	228.42	58.11	-36.94	-41.69	55.70	228.46	-0.09	0.06	0.01	0.11	0.08
magenta	48.70	72.20	0.30	72.20	0.24	49.13	72.05	-0.23	72.05	359.82	0.43	-0.15	-0.53	0.70	0.48
yellow	86.70	-6.90	96.20	96.45	94.10	87.65	-7.09	96.18	96.44	94.22	0.95	-0.19	-0.02	0.97	0.62
gray	50.40	1.60	4.10	4.40	68.68	50.83	1.71	4.09	4.43	67.31	0.43	0.11	-0.01	0.44	0.46
red	49.10	64.50	48.40	80.64	36.88	49.36	64.35	48.17	80.38	36.82	0.26	-0.15	-0.23	0.38	0.27
green	53.00	-62.90	36.60	72.77	149.81	53.57	-62.96	36.46	72.76	149.92	0.57	-0.06	-0.14	0.59	0.56
blue	25.80	21.80	-42.30	47.59	297.27	26.23	21.87	-42.23	47.56	297.38	0.43	0.07	0.07	0.44	0.33
brown	37.70	18.90	17.70	25.89	43.12	38.26	19.13	17.44	25.89	42.35	0.56	0.23	-0.26	0.66	0.56
purple	38.20	31.70	-15.10	35.11	334.53	38.60	31.64	-14.99	35.01	334.65	0.40	-0.06	0.11	0.42	0.35
pastel	63.10	29.30	25.00	38.52	40.47	63.47	29.15	24.95	38.37	40.56	0.37	-0.15	-0.05	0.40	0.32
										Aver.	0.34	0.02	-0.03	0.53	0.43
										St. Dev.	0.37	0.18	0.26	0.22	0.18

	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	*90.17*	*-0.25*	*3.64*	*3.65*	*93.93*	**-0.53**	**0.05**	**0.24**	**0.58**	**0.40**
black	13.10	0.60	0.60	0.85	45.00	*13.43*	*1.00*	*1.07*	*1.46*	*46.94*	**0.33**	**0.40**	**0.47**	**0.70**	**0.75**
cyan	58.20	-37.00	-41.70	55.75	228.42	*58.11*	*-36.98*	*-41.67*	*55.71*	*228.41*	**-0.09**	**0.02**	**0.03**	**0.10**	**0.08**
magenta	48.70	72.20	0.30	72.20	0.24	*49.27*	*72.07*	*-0.44*	*72.07*	*359.65*	**0.57**	**-0.13**	**-0.74**	**0.94**	**0.65**
yellow	86.70	-6.90	96.20	96.45	94.10	*87.75*	*-7.11*	*96.15*	*96.41*	*94.23*	**1.05**	**-0.21**	**-0.05**	**1.07**	**0.68**
gray	50.40	*1.60*	4.10	4.40	68.68	*50.71*	*1.68*	*4.08*	*4.41*	*67.62*	**0.31**	**0.08**	**-0.02**	**0.32**	**0.33**
red	49.10	64.50	48.40	80.64	36.88	*49.35*	*64.36*	*48.14*	*80.37*	*36.80*	**0.25**	**-0.14**	**-0.26**	**0.39**	**0.26**
green	53.00	-62.90	36.60	72.77	149.81	*53.46*	*-62.70*	*36.34*	*72.47*	*149.90*	**0.46**	**0.20**	**-0.26**	**0.56**	**0.46**
blue	25.80	21.80	-42.30	47.59	297.27	*26.26*	*21.87*	*-42.14*	*47.48*	*297.43*	**0.46**	**0.07**	**0.16**	**0.49**	**0.36**
brown	37.70	18.90	17.70	25.89	43.12	*38.25*	*19.17*	*17.70*	*26.09*	*42.72*	**0.55**	**0.27**	**0.00**	**0.61**	**0.50**
purple	38.20	31.70	-15.10	35.11	334.53	*38.64*	*31.74*	*-14.99*	*35.10*	*334.72*	**0.44**	**0.04**	**0.11**	**0.46**	**0.38**
pastel	63.10	29.30	25.00	38.52	40.47	*63.42*	*29.13*	*24.97*	*38.37*	*40.60*	**0.32**	**-0.17**	**-0.03**	**0.36**	**0.28**
										Aver.	**0.34**	**0.04**	**-0.03**	**0.55**	**0.43**
										St. Dev.	**0.38**	**0.19**	**0.30**	**0.27**	**0.19**

	X-RITE 530		D50/2-observer												
	L*	a*	b*	C*	h	L*	a*	b*	C*	h	DL	Da	Db	DE	DE00
white	90.70	-0.30	3.40	3.41	95.04	*90.24*	*-0.22*	*3.62*	*3.63*	*93.54*	**-0.46**	**0.08**	**0.22**	**0.51**	**0.36**
black	13.10	0.60	0.60	0.85	45.00	*13.49*	*0.99*	*1.04*	*1.44*	*46.35*	**0.39**	**0.39**	**0.44**	**0.71**	**0.74**
cyan	58.20	-37.00	-41.70	55.75	228.42	*58.20*	*-36.92*	*-41.62*	*55.64*	*228.43*	**0.00**	**0.08**	**0.08**	**0.11**	**0.03**
magenta	48.70	72.20	0.30	72.20	0.24	*49.27*	*72.15*	*-0.35*	*72.15*	*359.72*	**0.57**	**-0.05**	**-0.65**	**0.86**	**0.63**
yellow	86.70	-6.90	96.20	96.45	94.10	*87.67*	*-7.07*	*96.13*	*96.39*	*94.21*	**0.97**	**-0.17**	**-0.07**	**0.99**	**0.63**
gray	50.40	*1.60*	4.10	4.40	68.68	*50.70*	*1.73*	*4.14*	*4.48*	*67.25*	**0.30**	**0.13**	**0.04**	**0.33**	**0.35**
red	49.10	64.50	48.40	80.64	36.88	*49.34*	*64.32*	*48.23*	*80.39*	*36.86*	**0.24**	**-0.18**	**-0.17**	**0.34**	**0.24**
green	53.00	-62.90	36.60	72.77	149.81	*53.53*	*-62.85*	*36.48*	*72.67*	*149.87*	**0.53**	**0.05**	**-0.12**	**0.55**	**0.52**
blue	25.80	21.80	-42.30	47.59	297.27	*26.23*	*21.89*	*-42.22*	*47.55*	*297.41*	**0.43**	**0.09**	**0.08**	**0.44**	**0.33**
brown	37.70	18.90	17.70	25.89	43.12	*38.30*	*19.21*	*17.56*	*26.03*	*42.44*	**0.60**	**0.31**	**-0.14**	**0.68**	**0.57**
purple	38.20	31.70	-15.10	35.11	334.53	*38.56*	*31.81*	*-15.01*	*35.17*	*334.74*	**0.36**	**0.11**	**0.09**	**0.39**	**0.32**
pastel	63.10	29.30	25.00	38.52	40.47	*63.40*	*29.15*	*24.92*	*38.35*	*40.53*	**0.30**	**-0.15**	**-0.08**	**0.35**	**0.26**
										Aver.	**0.35**	**0.06**	**-0.02**	**0.52**	**0.42**
										St. Dev.	**0.35**	**0.18**	**0.26**	**0.25**	**0.20**

st devs									0.07	0.03
st devs									0.11	0.05
st devs									0.12	0.05
st devs									0.11	0.09
st devs									0.11	0.08
st devs									0.08	0.07
st devs									0.05	0.06
st devs									0.08	0.12
st devs									0.05	0.04
st devs									0.10	0.09
st devs									0.07	0.06
st devs									0.04	0.04
							averages		**0.02**	0.03
								repeatability		